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HEC-FDA Sensitivity and Uncertainty Analysis

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The U.S. Army Corps of Engineers software HEC-FDA is a tool that uses Risk-based Analysis to compute Expected Annual Damage (EAD) for flood damage reduction studies. EAD reduction is computed as the difference between EAD with and without alternative projects, a quantity used to aid in flood damage reduction project selection. Depending on the time and money spent in the collection and preparation of the input data sets, relatively lesser or greater accuracy can be achieved in EAD computation. Sets of numerical experiments on synthetic large and small drainage basins show that EAD is differently sensitive to the major input functions to HEC-FDA and their associated uncertainties depending on drainage area and the shape of the damage-stage curve. The results from the synthetic data sets are verified by two case studies on the Blue River, Missouri and the Chippewa River, Georgia. The relative sensitivity of EAD to its input functions and associated uncertainties can be used in federal investment decision-making for flood damage reduction projects.

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Appendix A. Numerical Results

Preface

This thesis was submitted by Mary Briant in partial satisfaction of the requirements for the degree of Master of Science in Civil Engineering at the University of California, Davis. All of the work was completed while Ms. Briant was a temporary employee at HEC. HEC-FDA Version 1.2 (March 2000) and a batch program version developed by Dr. David Goldman were used to perform the sets of model runs for the sensitivity and uncertainty analysis. The batch program version allowed the extraction of output not readily available from the Windows version. Dr. Goldman, an employee of HEC, also served as a member of the thesis committee. This thesis is published as an HEC research document in support of their efforts to further develop Risk-based Analysis and HEC-FDA.

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Executive Summary

The U.S. Army Corps of Engineers software HEC-FDA is a tool that uses Risk-based Analysis to compute Expected Annual Damage (EAD) for flood damage reduction studies. EAD reduction is computed as the difference between EAD with and without alternative projects, a quantity used to aid in flood damage reduction project selection. Depending on the time and money spent in the collection and preparation of the input data sets, relatively lesser or greater accuracy can be achieved in EAD computation. However, although the estimate can be improved, some parameter and model uncertainty is unavoidable. It is important to examine the sensitivity of EAD and EAD reduction to realistic differences in input functions and their associated uncertainties. These results can be used to identify factors with the least and greatest impact on the resulting EAD to make recommendations on the best investments to improve estimates of EAD and EAD reduction.

The current study addresses the following objectives using HEC-FDA:

- Examine and compare the sensitivity of Expected Annual Damage (EAD) and EAD reduction to variations in the three primary input functions, namely flow-exceedance probability, stage-flow and damage-stage.
- Examine and compare the sensitivity of EAD and EAD reduction to uncertainty in the three primary input functions.
- Identify the factors with the least and greatest uncertainty contribution to EAD.

- Use the results of the analyses to recommend the best investments in methods and data to improve flood damage analysis.

To examine possible differences in sensitivity and uncertainty between streams with different hydrologic, hydraulic and economic characteristics, 34 HEC-FDA data sets from across the continental United States and Hawaii were sorted according to drainage area and slope. Four categories were created to form a two by two matrix of drainage area and stream slope. Based on the information contained in the data sets according to this matrix, representative synthetic functions were created as base cases for a typical large drainage basin with flat stream slope and a typical small basin with steep stream slope.

For each category, the base case mean flow was taken from the middle of the sorted data sets, its standard deviation based on an assumed coefficient of variation of 0.5, and its skew assumed to be zero for an assumed Log Pearson Type III (LPIII) distribution of flood peaks. An appropriate stage-flow curve was generated based on a correlation developed between mean flow and stage-flow curve average slope. A damage-stage curve was generated based on typical curves in the sorted data sets and curves used in previous studies (Arnell, 1989; Beard, 1990). The proportion of total damage is used rather than total damage to put all analyses on the same economic basis.

For the sensitivity analysis, parameters were varied in each of the primary input functions to calculate EAD and EAD Reduction with 50, 100 and 250-year (0.02, 0.01

and 0.004 exceedance probability) levees. Mean, standard deviation and skew of the flow-exceedance probability function, y-intercept and vertical location of the stage-flow function, and lower and upper bounds and inflection point locations of the damage-stage function were varied. To examine sensitivity to uncertainty, equivalent record length and standard deviation of error about the stage-flow and damage-stage functions were varied. To complete the uncertainty analysis, the difference between the 0.25 and 0.75 exceedance values from the EAD distribution were extracted from the output to measure the uncertainty contribution from each input function. Based on the EAD calculated in each of the model runs, elasticity was calculated as the percent difference in EAD produced per percent change in the parameter being varied.

To test the results of the numerical experiments on the synthetic data sets, sensitivity to uncertainty was examined for two real sample data sets. A data set from a typical large drainage basin on the Blue River, Missouri and a data set from a typical small drainage basin on the Chippewa River, Georgia were used for comparison. The sample data sets served to verify results obtained from the synthetic data sets and expand the results to include damage-stage functions with different shapes.

The numerical experiments showed significant differences between the elasticity of EAD and EAD reduction for the large and small basins. Figure A summarizes the elasticity of EAD to parameters of its major input functions, and Figure B summarizes the elasticity of EAD to uncertainty.

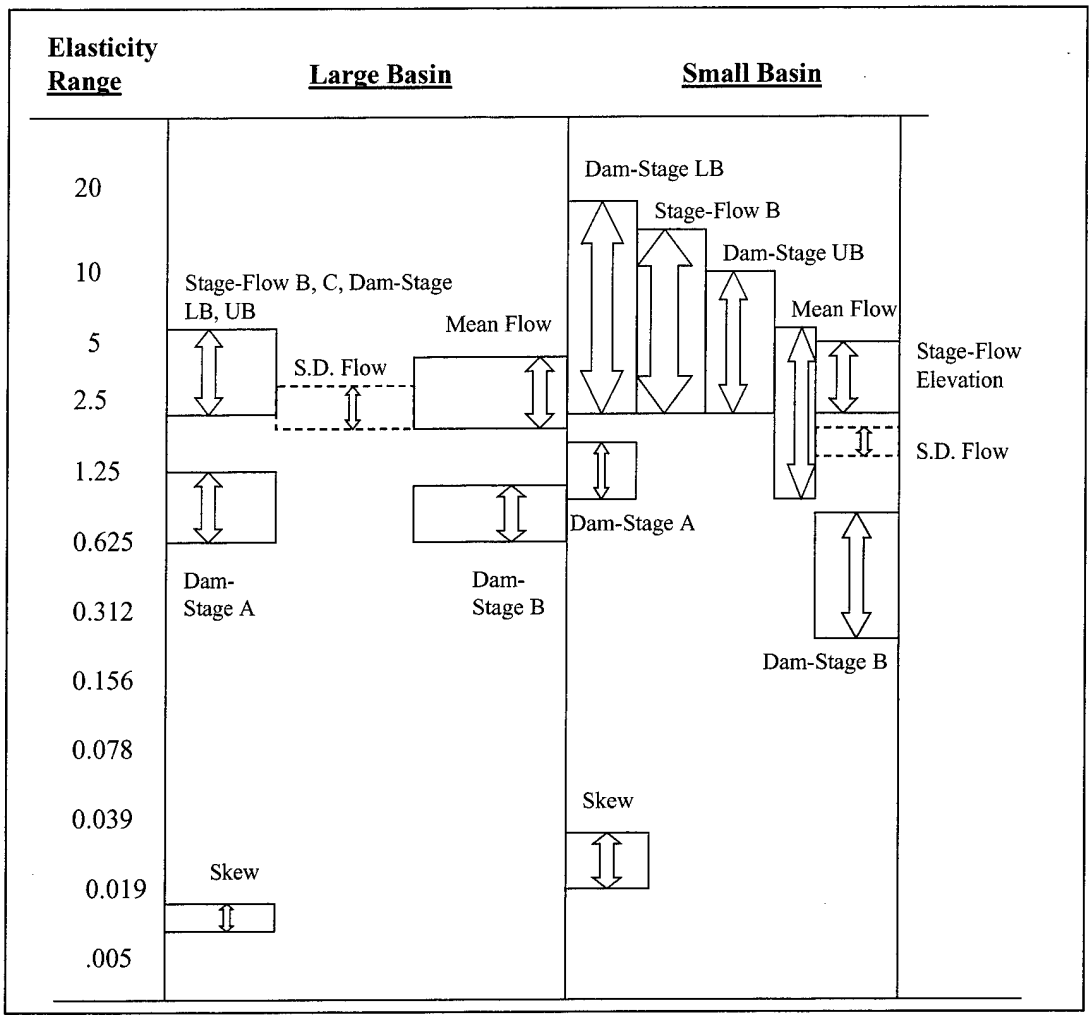

Figure A. Sensitivity Analysis Summary

Where Mean Flow = Mean flow of the flow-exceedance probability function; S.D. Flow = Standard deviation of flow-exceedance probability function; Skew = Skew of the flow-exceedance probability function; Stage-Flow B = Average slope of the stage-flow function; Stage-Flow C = Y-intercept of the stage-flow function; Dam-Stage LB/UB = Lower Bound/Upper Bound of damage-producing stages in the damage-stage function; Dam-Stage A/B = First and second inflection points in the damage-stage function.

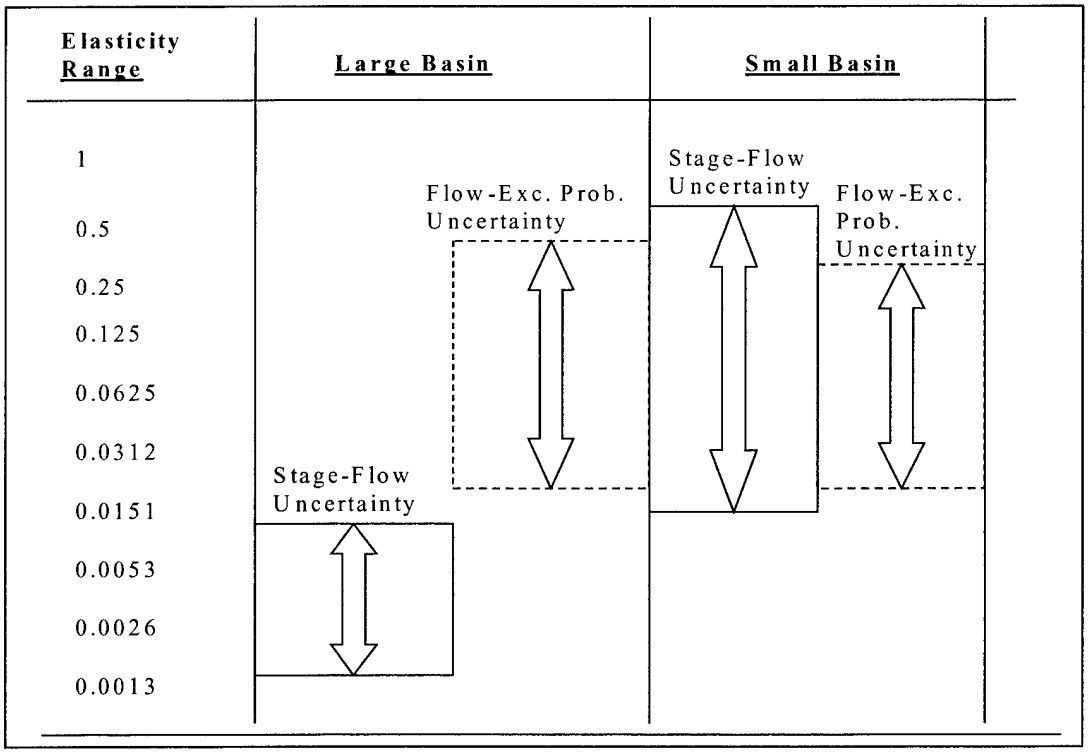

Figure B. Sensitivity to Uncertainty Analysis Summary

The results show that EAD and EAD reduction can be relatively sensitive to different variables over different ranges. EAD reduction is more sensitive to changes in function values for larger levees than for smaller levees. In general, EAD and EAD reduction are most sensitive to stage-flow function slope (depending on the basin area, shape of the stream channel and floodplain) and the upper and lower bounds of the damage-stage function (depending on the location, height and types of structures in the floodplain), and least sensitive to flow-exceedance probability skew (generally a regional characteristic). EAD and EAD reduction are generally more sensitive to uncertainty in flow-exceedance probability due to a limited flow record length than to stage-flow uncertainty due to rating curve scatter or uncertainty in Manning's n,

except for situations in a small basin with shorter flow record lengths and larger stage-flow uncertainty. It is most important to get an accurate estimate of the variables with the highest elasticity, such as stage-flow function shape, and least important to get an accurate estimate of the variables with the lowest elasticity, such as flow-exceedance probability skew. The value of additional information can be used in investment decision-making to estimate the benefits expected from improving median input function specification and reducing uncertainty.

Chapter 1

Introduction

The U.S. Army Corps of Engineers software HEC-FDA is a tool that uses Risk-based Analysis to compute Expected Annual Damage (EAD) for flood damage reduction studies. EAD reduction is computed as the difference between EAD with and without alternative projects, a quantity used to aid in flood damage reduction project selection. Depending on the time and money spent in the collection and preparation of the input data sets, relatively lesser or greater accuracy can be achieved in EAD computation. However, although the estimate can be improved, some parameter and model uncertainty is unavoidable. It is important to examine the sensitivity of EAD and EAD reduction to realistic variations in input functions and their associated uncertainties. These results can be used to identify factors with the least and greatest impact on the resulting EAD to make recommendations on the best investments for improving estimates of EAD and EAD reduction.

1.1 Objectives

The current study addresses the following objectives using HEC-FDA:

- Examine and compare the sensitivity of Expected Annual Damages (EAD) and EAD reduction to changes in the three primary input functions, namely flow-exceedance probability, stage-flow and damage-stage. This will be a sensitivity analysis as defined in (Morgan and Henrion, 1990, pg. 172), "methods for computing the effects of changes in inputs on model predictions".

- Examine and compare the sensitivity of EAD and EAD reduction to uncertainty in the three primary input functions.

- Identify the factors with the least and greatest contribution to EAD uncertainty. This will be an uncertainty analysis as defined in (Morgan and Henrion, 1990, pg. 172), "methods for comparing the importance of the input uncertainties in terms of their relative contributions to uncertainty in the outputs".
- Use the results of the analyses to recommend the best investments in methods and data to improve flood damage analysis.

1.2 Study Overview

This study examines the sensitivity of HEC-FDA results to the following parameters using a set of numerical experiments. The first three sets of experiments vary the shape of the input functions analytically, while the second three vary the specified uncertainty. Under each analysis, the following variables were varied directly:

1. Sensitivity to Flow Exceedance Probability Function
   - Mean Flow
   - Standard Deviation of Flow
   - Skew
2. Sensitivity to Stage-Flow Function
   - Slope of Stage-Flow Function
   - Y-intercept of Stage-Flow Function
3. Sensitivity to Damage-Stage Function

- Lower bound of damage-producing stages
- Upper bound of damage-producing stages
- Location of lower inflection point in function
- Location of upper inflection point in function

4. Sensitivity to Flow Exceedance Probability Uncertainty and Uncertainty Analysis
   - Equivalent Record Length
5. Sensitivity to Stage-Flow Uncertainty and Uncertainty Analysis
   - Standard Deviation of Error
6. Sensitivity to Damage-Stage Uncertainty and Uncertainty Analysis
   - Standard Deviation of Error

The numerical experiments listed above were conducted on synthetic base case functions typical of two general types of damage reaches – a flat stream with large drainage area and a steep stream with small drainage area. To test the results of the synthetic functions, the sensitivity to uncertainty experiments were conducted on two actual sample data sets. Sensitivity indices were developed to provide a consistent basis for comparison. The results of these numerical experiments were used to address the stated objectives.

Chapter 2

Background

2.1 EAD Computation by Direct Integration

Expected Annual Damage (EAD) has been calculated traditionally without explicit incorporation of uncertainty. To compute EAD, a flow-exceedance probability function is generated from a historical flow record, rainfall-runoff calculations or regional information; a stage-flow relationship is approximated from field measurements, water surface profile analysis or hydraulic routing; and a damage-stage relationship is approximated from records and surveys. For each exceedance probability, the corresponding flow is obtained from the flow-exceedance probability curve. The median stage associated with that flow is obtained from the stage-flow curve and the median damage corresponding to that stage is obtained from the damage-stage curve. After going through this process for a range of specified flow-exceedance probabilities, a damage-probability curve is generated. With direct integration, the area under the damage-probability curve yields expected annual damage. The difference in EAD between the with- and without-project conditions has been used to estimate the benefits expected from a project to aid in project selection. This process is illustrated in Figure 1 (USACE, 1989).

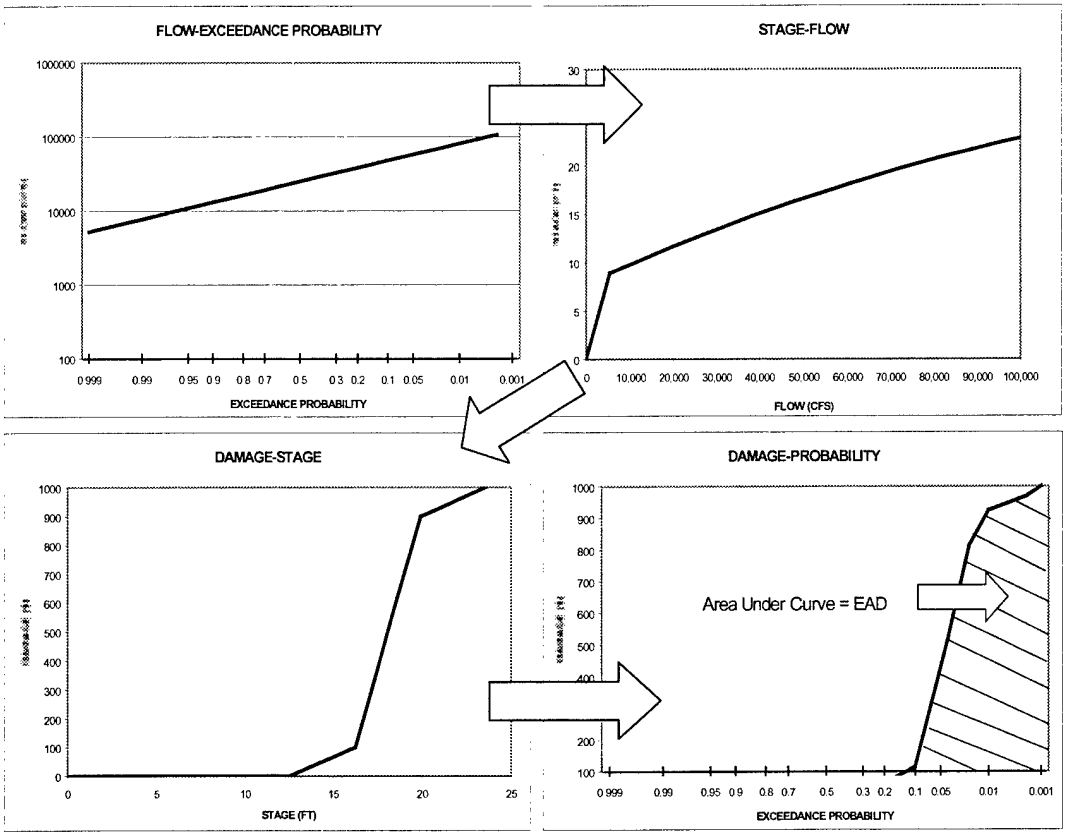

Figure 1. EAD Computation with Direct Integration

2.2 Expected Probability Estimator

The first efforts to include uncertainty in flood frequency and flood damage analysis resulted in the development of the expected probability estimator (Beard, 1960, 1978; Stedinger, 1983b). The expected probability estimator was developed to produce a better estimate of the true probability of occurrences over a broader scale (i.e., national) than a median estimator. For each quantile, the expected probability estimator provides an estimate of the mean probability of exceeding a flow level. The earliest work in developing the expected probability estimator was by Beard (1960), and refined in Guidelines For Determining Flood Flow Frequency, Bulletin #17B of

the Hydrology Subcommittee. The most current revised methods for computing an expected probability for hydrologic data are detailed in (IACWD, 1982).

2.3 Bayesian Inference

Bayesian inference has been advocated as a framework to incorporate uncertainty in federal investment decisions and flood frequency analysis for almost thirty years (Al-Futaisi and Stedinger, 1999; Bodo, 1976; Davis, 1972; Freer and Beven, 1996; Krzysztofowicz, 1983; Kuczera, 1999; Stedinger, 1983; Wood, 1975). Bayesian inference is a method of examining risk by considering a set of possible future statistics rather than only the statistics of the limited sample. In general, Bayes Theorem estimates the posterior distribution based on a prior distribution and likelihood function. Mathematically, Bayes Theorem can be summarized as the following:

$$f(\theta|x) = f(\theta) \cdot l(x|\theta) / \int (f(\theta) \cdot l(x|\theta)\, d\theta)$$

Where $l(x|\theta)$ is the likelihood of observation sequence x, $f(\theta)$ is the prior distribution, and $f(\theta|x)$ is the posterior distribution (Davis, 1972).

Limitations of Bayesian inference for forecasting include the informativeness of the prior distribution and the computational effort required. As informativeness of the prior distribution decreases, Bayesian analysis can become suboptimal unless procedures are used to account for an uninformative prior distribution. In general, the informativeness of the prior distribution depends on whether or not it is a representative sample of the population of values (Krzysztofowicz, 1983).

The likelihood function generally represents the analyst's degree of belief that a parameter has different values (Al-Futaisi and Stedinger, 1999). Using the prior distribution and likelihood function, the parameters of the posterior distribution are usually found by simulation. Posterior distribution parameters can be obtained by sampling from the likelihood function about the prior distribution. During simulation, the posterior distribution should become more peaked at the population value as the number of samples becomes large. Computational methods can be set up to allow updating of the prior distribution as information is obtained (Freer and Beven, 1996).

Krzysztofowicz (1983) demonstrates with Bayes Theorem that decision-makers that ignore uncertainty in probabilistic forecasts always incur an opportunity loss as the number of observations increases. Given that the amount of flow data and the number of federal investments in flood control are expected to continue to increase, the value of applying Bayesian Inference to flood damage analysis should increase. In light of this need to incorporate uncertainty in flood damage analysis in a systematic fashion, Risk-based Analysis has been under development.

2.4 Risk-Based Analysis Computation

In the evaluation of flood control projects, the variety of uncertainties makes it difficult to determine system performance under floods of varying magnitude. The USACE guidelines give the following operational definition of uncertainty (NRC, 1995):

Uncertainty: Uncertain situations are those in which the probability of potential outcomes and their results cannot be described by objectively known probability distributions, or the outcomes themselves, or the results of those outcomes are indeterminate.

For flood damage analysis, uncertainty cannot be described perfectly by objectively known probability distributions. However, uncertainty can be included explicitly in the analysis by assuming a best-fit probability density distribution to describe the range of likely functions. The parameters of the assumed distribution can be approximated from knowledge of the system, inferences from regional similar gaged basins and data collection. The U.S. Army Corps of Engineers' Risk-based Analysis incorporates uncertainty with best-fit distributions, as detailed below.

2.4.1 COMPUTATIONAL METHOD

The U.S. Army Corps of Engineers has incorporated uncertainty into flood damage analysis with the computer software HEC-FDA. HEC-FDA uses a Monte Carlo simulation to sample the interaction among the hydrologic, hydraulic and economic relationships and their individual uncertainties (USACE, 1996). The primary functions are flow-exceedance probability, stage-flow and damage-stage. Each relationship has a distribution of uncertainty about its median function, estimated from knowledge of the system and/or data collection and analysis methods. Random sampling from the range of likely flow-exceedance probability distributions, with the corresponding range of likely stage-flow and damage-stage probability distributions is repeated until the confidence limits of annual damages are not changed significantly

when more samples are taken. This sampling process results in an expected value of annual damage (HEC, 1998). A graphical summary of this method can be seen in Figure 2. The probability-density distribution of uncertainty about each function is shown with the input functions on the left, a sample iteration is shown in the middle and the resulting sample damage-probability function on the right. The area under the sample damage-probability curve produces one EAD sample for each iteration. The average of all samples produces a mean, or expected value of annual damage.

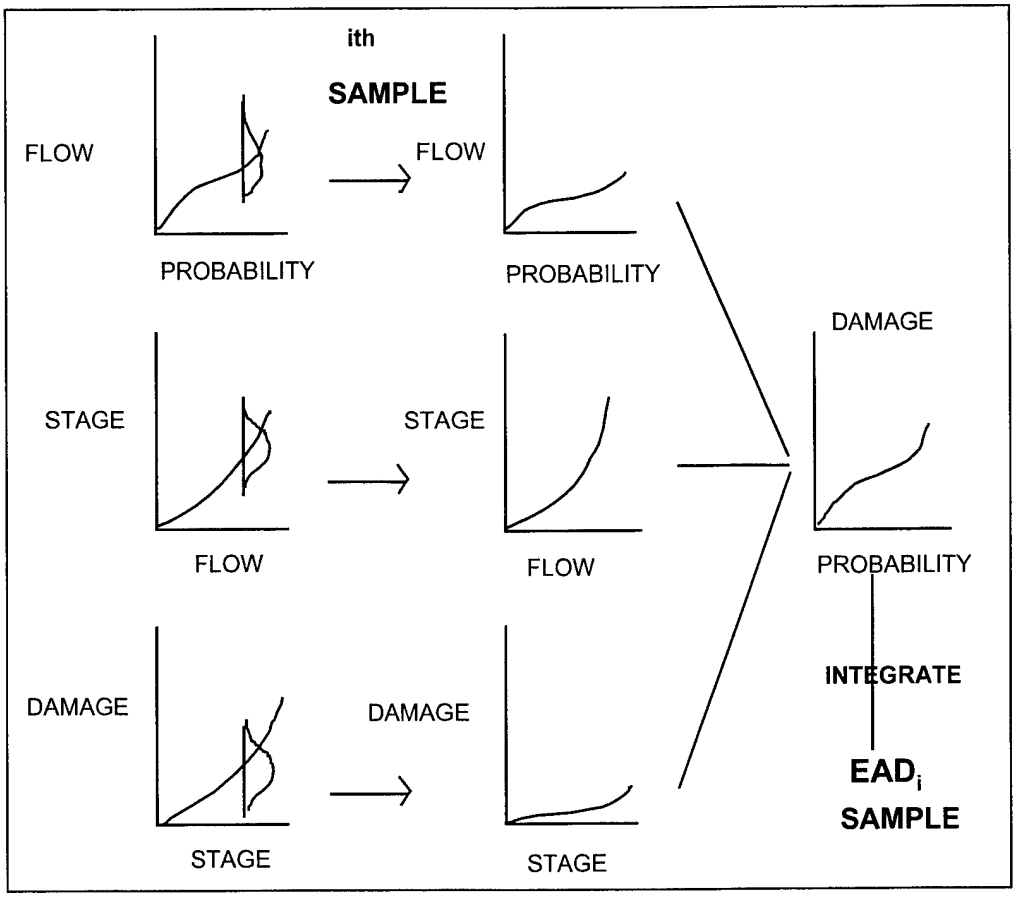

Figure 2. HEC-FDA Monte Carlo Analysis

2.4.2 FLOW-EXCEEDANCE PROBABILITY FUNCTION

The Water Resources Council published "Bulletin 17B, Guidelines for Determining Flood Flow Frequency" to promote a consistent approach to flood frequency analysis. In this publication, the Council recommends the use of the Log Pearson Type III (LPIII) distribution for flow frequency (IAWCD, 1982). Lindquist (1995) examined the effect of choosing different distributions to describe the flow frequency relationship and showed that the choice of distribution can have a significant effect on EAD. The LPIII describes the flow-exceedance probability distribution with three parameters, estimated using the method of moments. By adjusting these three moments, the LPIII is flexible enough to fit a wide variety of historical data sets (Lindquist, 1995). In HEC-FDA, data sets that are not described well by LPIII can be specified graphically (HEC, 1998). The graphical methods are commonly used for regulated flow conditions. However, for the purposes of setting up functions that can be altered systematically for sensitivity analysis, the LPIII distribution was used for the present study.

2.4.3 HYDROLOGIC UNCERTAINTY

Hydrologic uncertainty is represented by the distribution of error about the flow-exceedance probability function. The main source of hydrologic uncertainty is the limited historical flow data available at gaging stations. Most gaged locations have from 10 to 70 years of data, not all of which are completely reliable. Often, gages are washed out during the highest flow events, further limiting the accuracy of flood flow readings. In addition, there is greater uncertainty associated with the measurement of

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(4) TP-159 - "Some History and Hydrology of the Panama Canal"
(5) TP-160 - "Application of Risk-based Analysis to Planning Reservoir and Levee Flood Damage Reduction Systems"

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high flow, low frequency events and estimation of their associated exceedance probabilities than with more frequent flows (HEC, 1998). For an LPIII distribution of flood peaks, hydrologic uncertainty is included in flood damage analysis using a large sample approximation to the non-central t error distribution depending on gage record length (IAWCD, 1982; HEC, 1998). The USACE gives guidelines for approximating the equivalent record length for gaged and non-gaged locations. These guidelines are summarized in Table 1 (USACE, 1996b).

Table 1. Equivalent Record Length Guidelines

Method of Frequency Function Estimation	Equivalent Record Length[1]
Analytical distribution fitted with long-period gauged record available at site	Systematic record length
Estimated from analytical distribution fitted for long-period gauge on the same stream, with upstream drainage area within 20% of that point of interest	90% to 100% of record length of gauged location
Estimated from analytical distribution fitted for long-period gauge within same watershed	50% to 90% of record length
Estimated with regional discharge-probability function parameters	Average length of record used in regional study
Estimated with rainfall-runoff-routing model calibrated to several events recorded at short-interval event gauge in watershed	20 to 30 years
Estimated with rainfall-runoff-routing model with regional model parameters (no rainfall-runoff-routing model calibration)	10 to 30 years
Estimated with rainfall-runoff-routing model with handbook or textbook model parameters	10 to 15 years

[1] Based on judgement to account for the quality of any data used in the analysis, for the degree of confidence in models, and for previous experience with similar studies.

(USACE, 1996b)

For normal and log normal distributions, the non-central t distribution has been recommended for its flexibility in describing the sampling error distribution conditionally upon position along the flow-exceedance probability curve (IAWCD, 1982; Stedinger, 1983c; Tung, 1987; Chowdhury and Stedinger, 1991; Afshar, et al., 1994; Lindquist, 1995). A study by Bao, et al. (1987) concurs with these

recommendations and offers an extension to better incorporate skew in the uncertainty estimate.

The effects of hydrologic uncertainty on EAD were studied by Bao, et al. (1987) for normal, log normal, Pearson Type III (PIII), and LPIII flow-exceedance probability distributions. The results of this study show that EAD is very sensitive to hydrologic uncertainty, particularly for record lengths of less than 60 years. Results from Stedinger (1997) showed that damage estimates are significantly more sensitive to hydrologic uncertainty for record lengths of less than 50 years.

Although uncertainty due to a limited flow record is explicitly incorporated in HEC-FDA, uncertainty due to other factors is more difficult to quantify. Some studies have been completed to assess the relevance of long term climate change to flood control project planning. Venkatesh, et al. (1999) found that climate risk is of approximately the same importance as uncertainty in the damage-stage relationship in terms of the penalty suffered if it is ignored for Lake Erie, a lake with a large drainage area. However, Mendelsohn (1997) found that because basin-specific changes in runoff from global warming are currently uncertain and much delayed, most project analyses will be unaffected by global warming. Additional uncertainty is introduced if flood control dams change operations in the future or have surcharge capacity that was not included in the flood routing calculations. The amount of time flood water remains in the flood plain and recession characteristics are also uncertain due to variable drainage characteristics and human efforts (NRC, 1995). Although a method has not yet been

devised to explicitly incorporate all of these uncertainties, they are important to understand potential differences between model predictions and reality.

2.4.4 STAGE-FLOW FUNCTION

The stage-flow function is defined graphically in HEC-FDA based on field measurements and/or hydraulic calculations. Although there can be significant scatter in field measurements, the function is generally defined based on a single line of increasing stage with flow (Westphal, et al., 1999). However, this approximation becomes rougher with increasing flow, as is discussed below.

2.4.5 HYDRAULIC UNCERTAINTY

Hydraulic uncertainty is derived from the estimated relationship between flow and stage. Turbulence characteristics create variations in stage for a given flow while eroding the stream channel and changing the cross section (NRC, 1995). In light of this, higher flows possess greater hydraulic variability (and thus uncertainty) than medium and lower flows. Westphal, et al. (1999) demonstrate that the uncertainty introduced by unsteady, high flows was significant for the 1993 flood along the Mississippi River at St. Louis, Missouri. These results also imply a tendency towards hysteresis for extreme conditions, or stage-discharge relationships varying between the rising and falling hydrograph limb. However, the results of the Mississippi River study also found that neither changes in stage nor changes in flow rate correlate with short-term scour and fill at gauging sites (Westphal, et al., 1999).

Additional uncertainty in the stage-flow relationship is introduced by variation in flow-stage measurements, ice, debris, bulking, seasonal variations in Manning's n value, structural integrity, multiple possible failure modes, and surveying inaccuracies of levees and water control structures (Burnham, pers. com., 2000). Settling of levees and subsidence of flood plain lands over time also can be a factor. Simplifications made for hydraulic calculations such as averaging flow resistance characteristics and limiting the number of cross sections and their associated survey measurement errors also contribute to hydraulic uncertainty (NRC, 1995). Guidelines for estimating a standard deviation of error of the hydraulic uncertainty distribution depending on survey methods are given in HEC (1986) as part of a detailed analysis on the sources of stage-flow error. The study found that uncertainty in Manning's n is the greatest contributor to stage-flow error, although it is not apparent exactly how it affects the variance of that error (HEC, 1986).

The best-fit distribution of stage-flow uncertainty can vary with how the relationship was estimated. The scatter about the best-fit stage-flow curve estimated at a gaged reach can be approximately normal or more skewed. Freeman et al. (1996) found that the gamma distribution can represent a wide range of rating curve error distributions from normal to highly skewed, and recommended it to describe stage uncertainty (USACE, 1996b). Methods for approximating the uncertainty for ungaged stream reaches based on measurable stream parameters and computed water surface profiles are detailed in USACE (1996b). For ease of sensitivity analysis with HEC-FDA, the normal distribution was used to approximate stage-flow uncertainty, with the range of

standard deviations of error determined based on Manning's n reliability (USACE, 1996b).

2.4.6 DAMAGE-STAGE FUNCTION

The damage-stage function is calculated as a graphical function based on procedures described in the "National Economic Development Procedures Manual – Urban Flood Damage", March 1988, "National Economic Development Procedure Manual – Urban Flood Damage – Volume II: Primer on Surveying Flood Damage for Residential Structures and Contents", October 1991, "Catalog of Residential Depth-Damage Functions", May 1992, and "Analysis of Non-Residential Content Value and Depth-Damage Data for Flood Damage Reduction Studies", April 1996 (HEC, 1998). The general shape of the damage-stage function usually varies between a straight line and S-shaped curve, depending on land use characteristics (Arnell, 1989). The most common shape in the U.S. is most similar to the "logistic", or "S" shape from Arnell (1989), with the steepest part of the curve between the 100-year and 1,000-year stages (Beard, 1990). Al-Futaisi and Stedinger (1999) used a quadratic equation to describe the damages above a certain threshold. A quadratic equation was not used for this study due to the difficulty in systematically applying changes in function shape to represent a realistic range of conditions to be examined for the sensitivity analysis.

2.4.7 DAMAGE UNCERTAINTY

Uncertainty associated with the damage-stage relationship can be calculated based on the individual uncertainties of its major components. Currently, HEC-FDA can account for uncertainty in structure value, content to structure value ratio, depth-

percent damage and surveyed elevations. These uncertainties are combined into an estimated normal, triangular, or log normal distribution of error about the mean (HEC, 1998). The standard deviation of this error distribution is usually specified as a percentage of the damages (Moser, 1993). However, Lindquist (1995) showed that the distribution of damage error does not affect the calculation of EAD as long as the mean function is specified. The distribution of uncertainty is only significant if the distribution of EAD is under examination.

The error distribution does not account for any changes in velocity (and water surface elevation) as the floodwater spreads onto the flood plain, or the accumulation of debris that can affect water stage and damage at different locations. The distribution also does not account for any differences in water stage between the surrounding flood plain and individual structures. The way in which the duration of flooding affects damage is also not considered (NRC, 1995). However, a study by Afshar, et al. (1998) assumed that the effects of flooding time and volume are minor for structure/building flood damage estimation. Additional factors that influence flood damage are described in USACE (1996b).

Although these sources of uncertainty are difficult to quantify for inclusion in the distribution of uncertainty, they contribute to differences between the model approximation and reality. Although it might seem ideal to try to quantify and include all conceivable sources of uncertainty in its distribution, it is important to realize that increasing complexity does not necessarily yield an increase in accuracy (Pilgrim,

1986). Therefore, it is desirable to consider a best estimate of the range of possible distributions without breaking the distribution down into too many small pieces.

2.5 Comparison of Methods

While all methods share the goal of estimating expected annual damage to compare flood damage reduction alternatives, Direct Integration, Expected Probability and Risk-based Analysis differ in assumptions about the most accurate way to perform flood damage analysis under imperfectly known conditions. More detailed discussion on the controversial appropriate use and role of these methods has been published in an ongoing series of papers (Beard, 1960, 1978, 1990, 1997, 1998; Thomas, 1976; NRCTF, 1978; Stedinger, 1983; Arnell, 1989; Gunasekara and Cunnane, 1991; Rasmussen and Rosbjerg, 1991; Stedinger, 1997; Goldman, 1997). While Direct Integration computes the median annual damage without explicitly considering uncertainty, Risk-based Analysis computes the mean annual damage (expected value) with probability density distributions of likely input functions. Since the expected probability method estimates a mean damage, the method is inherent in the risk-based approach. The higher value of the mean relative to the median in a positively skewed uncertainty distribution yields a generally higher EAD. A schematic of the positively skewed hydrologic uncertainty distribution is given in Figure 3.

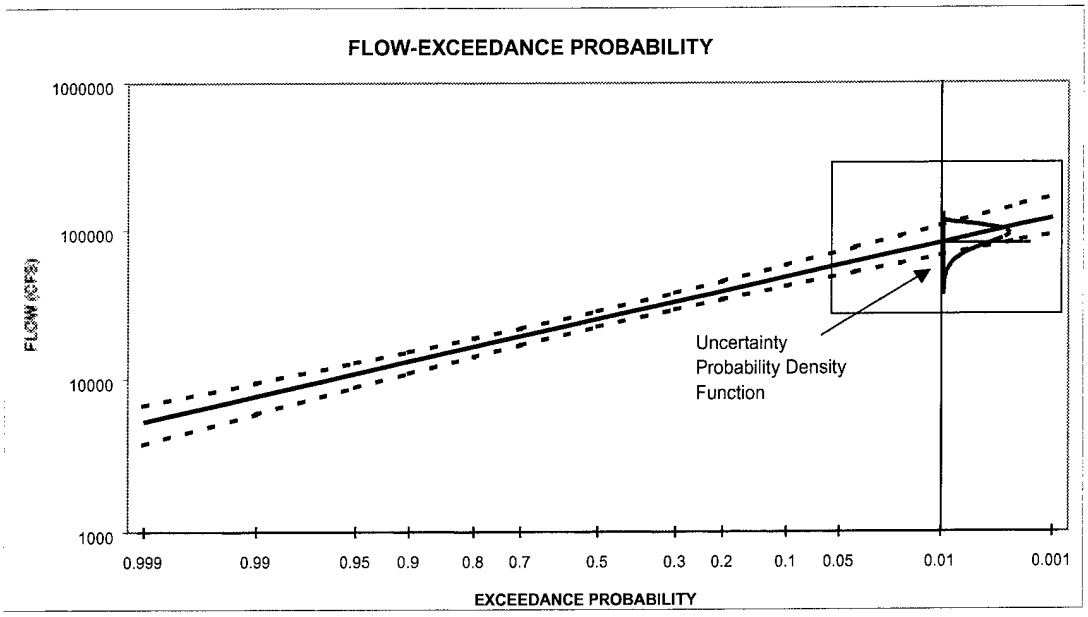

Figure 3. Skewed Hydrologic Uncertainty Distribution Schematic

For Risk-based Analysis, the benefits of explicitly incorporating uncertainty in the EAD calculation can be estimated using the concept of the expected value of including uncertainty (EVIU). EVIU is the difference between the expected value of the optimal decision with uncertainty considered and the expected value of the optimal decision with uncertainty ignored (Morgan and Henrion, 1990). For flood damage analysis, this can be defined as:

$EVIU = [EAD_{U,wo} - EAD_{U,w}] - [EAD_{wo} - EAD_{w}]$

where

$EAD_{U,wo}$ = Expected Annual Damage including uncertainty, without project

$EAD_{U,w}$ = Expected Annual Damage including uncertainty, with project

EAD_{wo} = Expected Annual Damage without considering uncertainty, without project

EAD_{w} = Expected Annual Damage without considering uncertainty, with project.

Risk-based Analysis also allows estimation of the value of additional information, the difference between the confidence in the flood damage estimate with current information, and the confidence in the flood damage estimate if one more unit of information was obtained in any of the primary input functions (Morgan and Henrion, 1990). An extension of the value of additional information is the difference between the current net benefits expected from a project and the net benefits expected if one more unit of information was obtained. The concepts of EVIU and value of additional information can be used along with the results of the current study in investment decision-making. The following section presents a detailed description of the approach used to address the current study objectives.

Chapter 3

Analysis Approach

3.1 Base Case Functions

To examine possible differences in sensitivity and uncertainty between streams with different hydrologic, hydraulic and economic characteristics, 34 HEC-FDA data sets from across the continental United States and Hawaii were sorted according to drainage area and slope. Four categories were created to form a two by two matrix of drainage area and stream slope. The distribution of data sets within the matrix can be seen in Table 2.

Table 2. HEC-FDA Data Set Matrix

Stream Type	Small Drainage Area ($<100 mi^2$)	Large Drainage Area ($>100 mi^2$)
Flat Stream Slope (<3 ft/mi.)	Coulee des Cannes, LA Chester Creek, PA	Lafayette/Vermilion R., LA Ocmulgee River, GA Blue River, MO Chattahoochee River, GA Flint River, GA White Oak Bayou, TX Willamette River, OR DesPlaines River, IL Cumberland River, OH Tygart River, WV Sheyenne River, ND Etowah, GA Tuolumne River, CA Missouri River, MO
Steep Stream Slope (>3 ft/mi.	Harmon Canal, GA Wailupe, HI Perry Creek, IA Strong Ranch Slough, CA Deer Creek, MN Anacostia River, VA NW Anacostia, VA Lower Mission Cr, CA Antelope Cr, NE Beargrass Cr, KY Rio De Flag, AZ Warm Springs, CA	Pecan Bayou, TX Tres Rios/Gila River, AZ Murrieta Creek, CA Scranton/Lackawanna R., PA Greens Bayou, LA White River, IN

Small and large drainage areas were divided at 100 square miles, and steep and flat stream slopes were divided at 3 feet/mile. Since most of the data sets fell into one of two categories (large drainage area/flat slope or small drainage area/steep slope), representative synthetic functions were created as base cases for these two categories. Examination of cases in the other two categories can be included in further study. The following procedures were used to generate representative base case functions.

3.1.1 FLOW-EXCEEDANCE PROBABILITY FUNCTION

Within each category, the flow-exceedance probability function for each data set was plotted. The range of mean flows typical to the two categories of interest can be seen in Tables 3a and 3b.

Table 3a. Flow-Exceedance Probability Function of Known Large/Flat Data Sets

Large/Flat Data Set	Mean Flow (cfs)
Illinois River, IL	430
Lafayette/Vermilion, LA	952
Sheyenne River, ND	1,200
DesPlaines R, IL	2,555
Tuolumne R, CA	5,000
Etowah R, GA	8,283
Blue River, MO	10,170
White Oak Bayou, TX	12,271
Chattahoochee R, GA	21,702
Ocmulgee River, GA	26,448
Tygart River, WV	26,696
Flint River, GA	31,623
Cumberland River, OH	96,694
Willamette River, OR	136,994
Missouri River, MO	214,042

Table 3b. Flow-Exceedance Probability Function of Known Small/Steep Data Sets

Small/Steep Data Set	Mean Flow (cfs)
Rio De Flag, AZ	19
Warm Springs, CA	70
Beargrass Cr, KY	401
Lower Mission Cr, CA	500
Deer Creek, MN	534
Harmon/Chippewa, GA	707
Strong Slough, CA	788
Wailupe, HI	949
Antelope Cr, NE	1,900
Perry Creek, IA	2,180
NW Anacostia R, VA	4,410
Anacostia R, VA	5,154

For consistency with Bulletin 17B recommendations and ease of sensitivity analysis, base case functions were created as Log Pearson Type III with zero skew, or Log Normal (IAWCD, 1982). The mean flow for each base case was chosen from the middle of the known data sets in its respective category. For the large drainage area/flat stream, a mean flow of 25,000 cfs was used. For the small drainage area/steep stream, a mean flow of 700 cfs was used. The coefficient of variation (COV) is the ratio of the standard deviation to the mean of a distribution. Linsley (1986) reports a typical range of 0.3 – 0.8 for the COV of floods in the United States in real space, while Al Futaisi and Stedinger (1999) and Landwehr (1978) report a typical range of 0.5 – 1.0. Assuming the range stated by Al Futaisi and Stedinger (1999) and Landwehr (1978), the COV is between 0.05 and 0.13 in log space. In general, arid regions tend to have a higher COV, whereas wetter regions tend to have a lower COV (Landwehr, 1978). A COV of 0.05 was assumed for each base case in log space to represent a climate with less flow variability. A COV of 0.05 yields a standard deviation of 0.22 for the large/flat case and 0.14 for the small/steep case. The

resulting base case functions are shown in Figure 4. To minimize uncertainty, the equivalent record length was assumed to be 200 years.

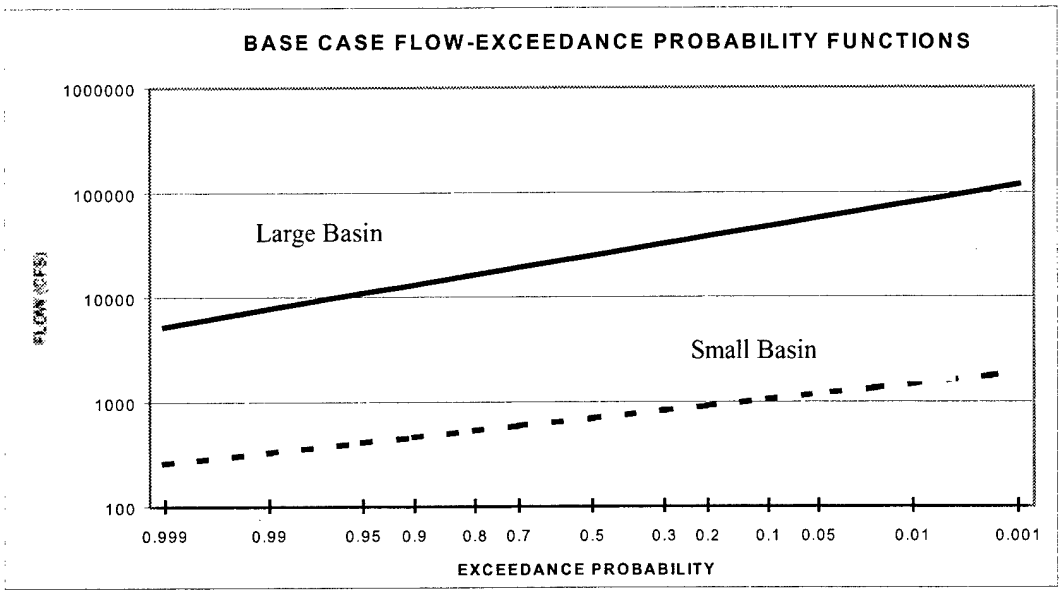

Figure 4. Base Case Flow-Exceedance Probability Functions

3.1.2 STAGE-FLOW FUNCTION

To create base case stage-flow functions consistent with the flow-exceedance probability functions, the stage-flow functions from the known data sets were plotted. A quadratic function was fitted to the data points for flows greater than zero. The function is connected via a straight line to (0,0). The average slopes of each function were plotted against the mean flow from the corresponding flow-exceedance probability function to approximate a correlation.

Based on the plot scatter for the small/steep case, the corresponding rating curve can have an approximate slope of 0.002 to 0.006. Based on the plot scatter for the large/flat case, the corresponding rating curve can have an approximate slope of 0.0001 to 0.0005. The correlations can be seen in Figures 5a and 5b. Based on the

range of y-intercept values for the appropriate case functions, the y-intercept ("C" value) can vary between 0 and 5 for the small/steep case and between 5 and 10 for the large/flat case. The range of flows covered by the stage-flow function must meet or exceed the range of flows in the flow exceedance probability function. To minimize uncertainty in the base cases, the standard deviation of error was set to 0.01 feet. The resulting base case stage-flow functions are (See Figure 6):

Small/Steep:

$Y = -6E\text{-}7X^2 + 0.004X + 1.55$

Large/Flat:

$Y = -5E\text{-}10X^2 + 0.0002X + 7.89$

where Y = Stage (ft) and X = Flow (cfs).

For flows higher than the apex of the curve, a linear approximation was used with a slope equal to the slope of the 500 cfs prior to the apex.

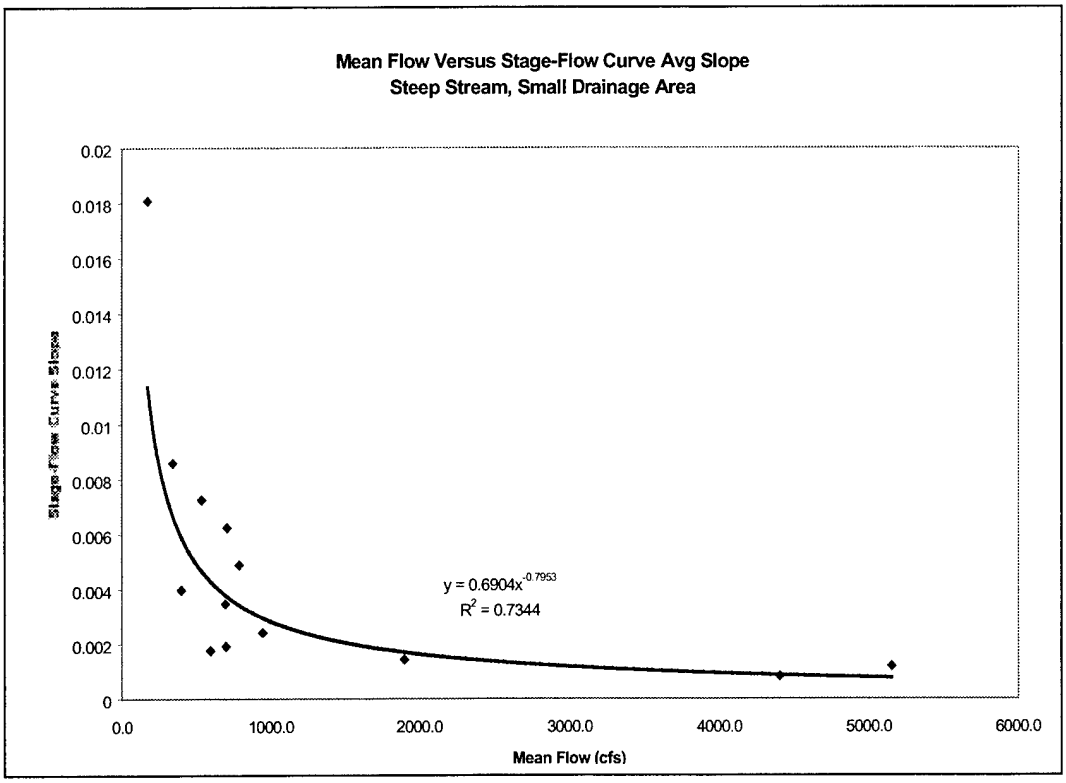

Figure 5a. Mean Flow – Stage-Flow Curve Average Slope Correlation: Steep Stream, Small Drainage Area

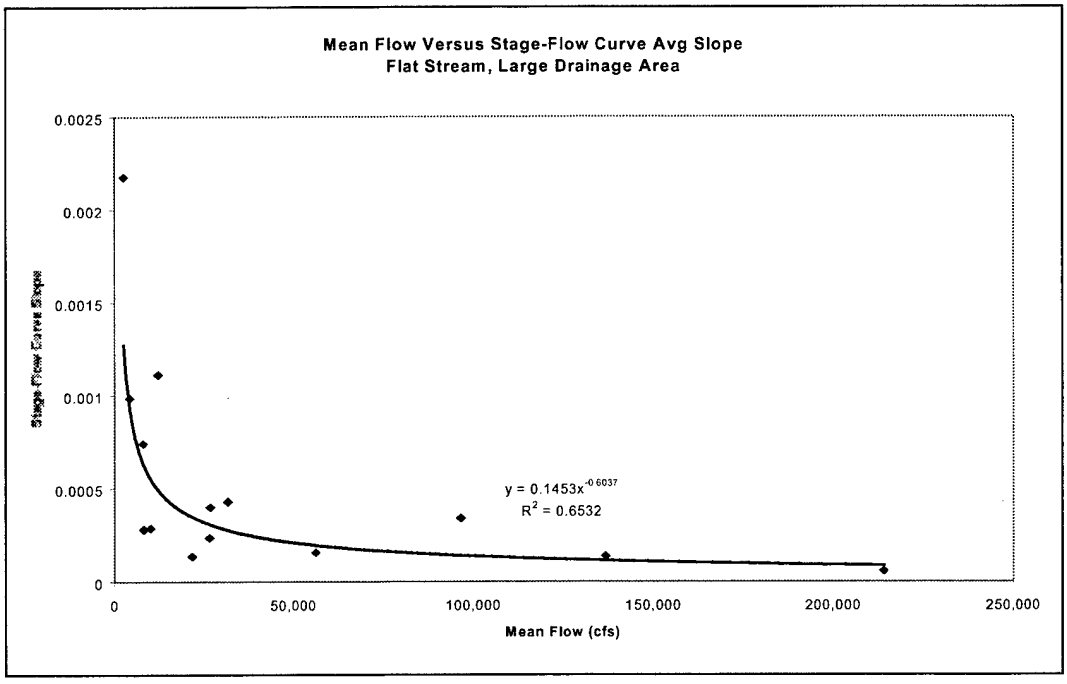

Figure 5b. Mean Flow – Stage-Flow Curve Average Slope Correlation: Flat Stream, Large Drainage Area

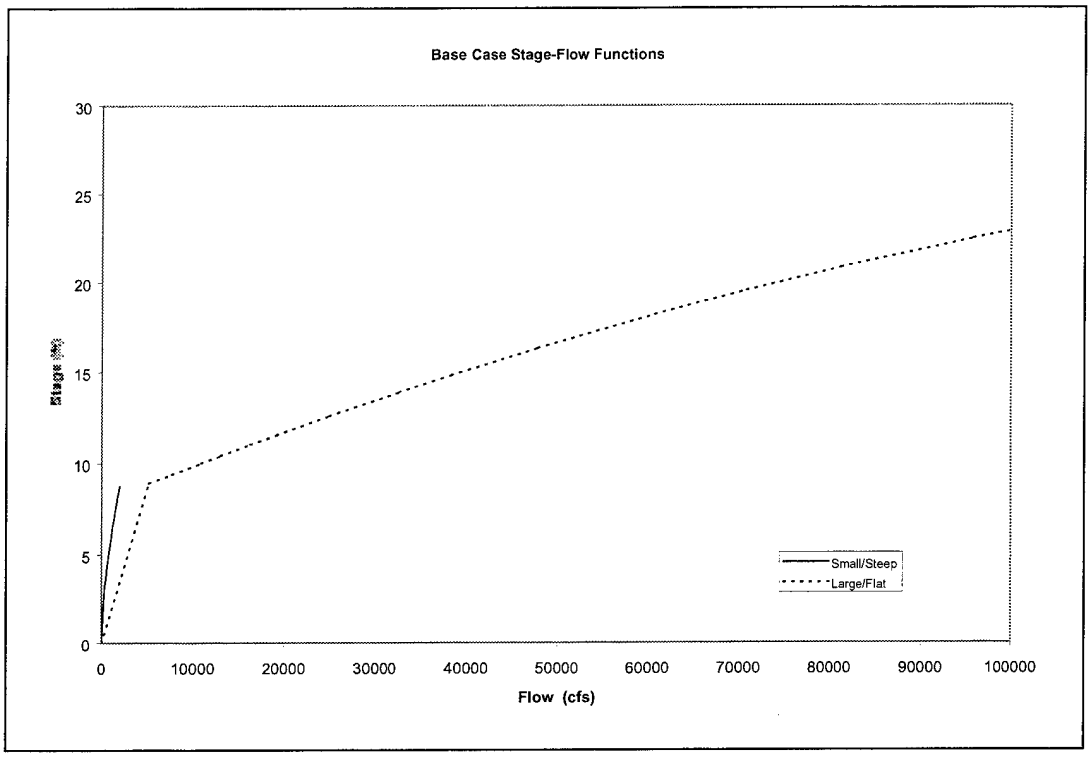

Figure 6. Base Case Stage-Flow Functions

3.1.3 DAMAGE-STAGE FUNCTION

Like the first two functions, the damage-stage functions were created by first plotting the damage-stage functions of the known data sets. Based on the typical shapes of the known functions and studies by Arnell (1989) and Beard (1990), a piecewise linear function was created to allow the functions to be more easily and systematically adjusted during the set of runs necessary for sensitivity analysis. The piecewise linear shape is most closely related to the "logistic" shape in Arnell (1989), and recommended by Beard (1990) as the most common curve shape for floodplains in the U.S. Assuming damage begins at the mean stage associated with the 2-year event (exceedance probability = 0.5) and maximizes at the mean stage associated with the

500-year event (exceedance probability = 0.002), the following typical function was derived:

Between X=0 and X=LB, Y=0

At X=1/3(UB-LB) + LB, Y=0.1

At X=2/3(UB-LB) + LB, Y=0.9

At X=UB, Y=1

where Y = Proportion of Total Damage (between 0 and 1); X = Stage (ft)

LB = Lower Bound Stage of Damage Function; UB = Upper Bound Stage of Damage Function.

The proportion of total damage is used rather than total damage to put all analyses on the same economic basis. To minimize uncertainty for the base case, the standard deviation of error was set to 0.01 feet. The base case damage-stage functions can be seen in Figure 7.

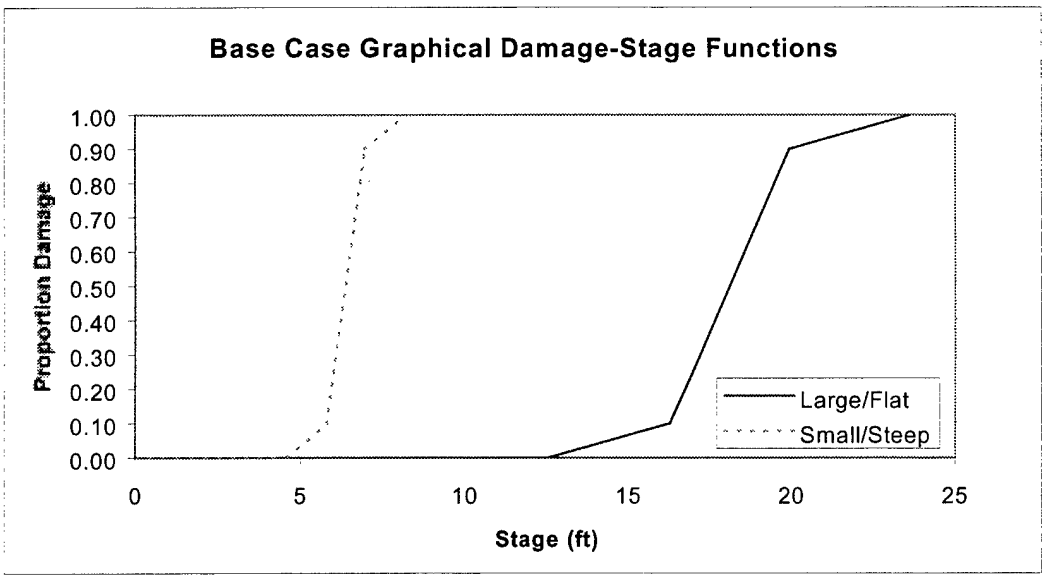

Figure 7. Base Case Damage-Stage Functions

3.2 Sensitivity Analysis

3.2.1 FLOW-EXCEEDANCE PROBABILITY FUNCTION

To examine the effects of changing the shape of the most likely flow-exceedance probability function on EAD and EAD reduction, the three parameters of the Log Pearson Type III function were varied independently. Table 4 summarizes the variation introduced to the flow-exceedance probability function to examine the sensitivity of EAD and EAD reduction to flow-exceedance probability function parameters.

Table 4. Flow-Exceedance Probability Function Sensitivity Analysis

Base Case	Variable	Base Value	Lower Limit	Upper Limit	Increment
Large/Flat	Mean	25,000 cfs	12,500 cfs	25,000 cfs	500 cfs
Small/Steep	Mean	700 cfs	350 cfs	700 cfs	50 cfs
Large/Flat	SD (log)	0.22	0.22	0.57	0.1
Small/Steep	SD (log)	0.14	0.14	0.37	0.1
Large/Flat	Skew (log)	0	-0.7	0.4	0.1
Small/Steep	Skew (log)	0	-0.7	0.4	0.1

The range in mean values was chosen to keep a reasonable coefficient of variation according to Landwehr (1978) without having to change the standard deviation. Accordingly, the range in standard deviation values was chosen to yield a reasonable range in coefficient of variation. The range of skew values was based on the USGS map of Generalized Skew Coefficients of Logarithms of Annual Maximum Streamflow by One Degree Quadrangles (IACWD, 1982).

3.2.2 STAGE-FLOW FUNCTION

The base case stage-flow function was created as a quadratic equation so its coefficients could be varied systematically. The function is of the form:

$S = aQ^2 + bQ + c$

where S = Stage (ft) and Q = Flow (cfs).

To vary the function slope, "b" was varied. To vary the function vertically, "c" was varied. Table 5 shows the method used to examine the sensitivity of EAD and EAD reduction to variation in the stage-flow function.

Table 5. Stage-Flow Function Sensitivity Analysis

Base Case	Variable	Base Value	Lower Limit	Upper Limit	Increment
Large/Flat	b/Slope	0.0002	0.0001	0.0005	0.0001
Small/Steep	b/Slope	0.0048	0.002	0.006	0.001
Large/Flat	c/Y-Int.	7.89	5	10	1
Small/Steep	c/Y-Int.	1.55	0	5	1

It is important to note that the function type assumed does not account for reverse flow conditions. Such conditions can result from a combination of backwater effects (from tides or larger order streams), intense precipitation and high flows. Reverse flow conditions are generally rare except in flat streams. For example, this situation occurs along the Vermilion River in Louisiana (USACE, 1995). In this case, it is important to have the rating curve reflect a probability weighted average condition useful for transforming the flow-exceedance probability curve to a stage-exceedance probability curve (Goldman, pers. comm., 2000).

3.2.3 DAMAGE-STAGE FUNCTION

The base case damage-stage function was created as a piecewise linear function to allow systematic variation. Fitting polynomial functions to data points as was done for the stage-flow function proved inadequate to properly describe the damage-stage function shapes while coefficients were varied. For the piecewise linear function,

inflection points in the function were specified according to the following general function:

Between X=0 and X=LB, Y=0

At X = A(UB-LB) + LB, Y=0.1

At X = B(UB-LB) + LB, Y=0.9

At X = UB, Y=1

where Y = Proportion of Total Damage (between 0 and 1)

X = Stage (ft)

A = Location of first inflection point (as fraction of total range of damage-producing stages)

B = Location of the second inflection point

LB = Lower Bound Stage of Damage Function

UB = Upper Bound Stage of Damage Function.

For the base case, A=1/3 and B=2/3 for the flat/large and steep/small cases. For sensitivity analysis, the lower bound stage, upper bound stage, A and B were varied to examine the sensitivity to overall slope of the function and slopes of three main sections of the function. Table 6 summarizes the method used to examine the sensitivity of EAD and EAD reduction to differences in the damage-stage function.

Table 6. Damage-Stage Function Sensitivity Analysis

Base Case	Variable	Base Value	Lower Limit	Upper Limit	Increment
Large/Flat	LB	12.6	8.6	16.6	1
	UB	23.6	19.6	27.6	1
	A	1/3	1/6	3/6	1/6
	B	2/3	3/6	5/6	1/6
Small/Steep	LB	4.2	2.2	4.2	1
	UB	8.2	6.2	8.2	1
	A	1/3	1/6	3/6	1/6
	B	2/3	3/6	5/6	1/6

LB = Lower bound of damage-producing stages, UB = Upper bound of damage-producing stages, A = Location of first inflection point (as fraction of total range of damage-producing stages), B = Location of second inflection point

3.3 Sensitivity to Uncertainty

In addition to examining the sensitivity of EAD and EAD reduction to differences in the shape of the input functions, its sensitivity to differences in uncertainty was examined. In HEC-FDA, uncertainty can be specified in each of the three primary input functions. Flow-exceedance probability uncertainty is estimated as a function of the sampling error in the mean and standard deviation. The uncertainty in the mean is known to be described by a normal distribution and the standard deviation by a chi-squared distribution (Goldman, pers. comm., 2000). Stage-flow uncertainty and damage-stage uncertainty are assumed to be described by a normal distribution. To examine sensitivity to parameter uncertainty, the base case functions were used with minimal uncertainty. Uncertainty was estimated and introduced in increments for each function.

3.3.1 FLOW-EXCEEDANCE PROBABILITY UNCERTAINTY

To examine the sensitivity of EAD and EAD reduction to flow-exceedance probability uncertainty, the equivalent record length was varied between 10 years and 200 years for each base case. As equivalent record length increased, uncertainty and the standard deviation of error decreased. For a given equivalent record length, the amount of uncertainty increases with flow. Therefore, the flat/large case possessed greater uncertainty than the steep/small case for the same equivalent record length.

As is discussed in the previous section, the sampling error in estimates of the mean and standard deviation is used to describe parameter uncertainty (Stedinger, 1983b). When skew is included in the flow-exceedance probability distribution, the calculation extension provided by Bao, et al. (1987) is needed to provide a better estimate of parameter uncertainty.

Sources of error other than a limited historical record length can be considered in estimating uncertainty in the flow-exceedance probability distribution. Kuczera (1996) presents the results of rating curve error on flood frequency inference. If the flood flow-exceedance probability distribution is back calculated from stage measurements and a rating curve, the flow-exceedance probability distribution contains some error in addition to the error introduced by a limited record length. The error introduced by flood frequency inference can be incorporated into estimation of equivalent record length as described by USACE (1996b). Other methods of estimating flow frequency such as hydrologic modeling or estimation from other gages

within the watershed also can be incorporated into the equivalent record length (USACE, 1996).

3.3.2 STAGE-FLOW UNCERTAINTY

To examine the sensitivity of EAD and EAD reduction to stage-flow uncertainty, the standard deviation of error about the mean function was varied. The standard deviation of error was assumed to increase linearly with flow, with zero uncertainty at (0,0). The error was assumed to remain constant above the 0.01 exceedance probability (100-year) event. EAD and EAD reduction were calculated for standard deviation of error equal to 0.3, 0.6, 1.5 and 3.0 feet to represent varying accuracy in data. These standard deviations account for likely ranges of error introduced by survey technology limitations, selected accuracy, Manning's roughness coefficient, and stream hydraulic properties for steady flow (HEC, 1986).

The effects of unsteady flow characteristics become more important at higher flows. Westphal, et al. (1999) demonstrate that the uncertainty introduced by unsteady, high flows was significant for the 1993 flood along the Mississippi River at St. Louis, Missouri. These results also imply a tendency towards hysteresis for extreme conditions. Unsteady flow effects were not considered in the current study since neither of the typical cases developed had high enough flows to magnify unsteady flow effects to the degree demonstrated by the Mississippi River study (Westphal, et al., 1999).

3.3.3 DAMAGE-STAGE UNCERTAINTY

Sensitivity to damage-stage uncertainty was examined in a similar manner to stage-flow uncertainty. A normal distribution was assumed to describe the uncertainty, with the standard deviation of error about the mean variable. The standard deviation of error was assumed to increase linearly with stage, with zero uncertainty at (0,0). Due to the intense data requirements of doing a rigorous derivation of the damage-stage function, the effect of large variances in damages were examined as recommended by Lindquist (1995). EAD and EAD reduction were calculated for standard deviation of error equal to 5%, 10% and 20% of the mean damage value.

Venkatesh and Hobbs (1999) assumed a uniform uncertainty distribution for a study to compare the effects of climate uncertainty with damage uncertainty at Lake Erie. The uniform distribution had 1/3 probability that the damage-stage curve will be 50% lower than its expected value, 1/3 probability that the damage-stage curve will be 50% higher than its expected value, and 1/3 probability that the damage-stage curve will be equal to its expected value. This assumption is different than for the present study in that the present study assumes that enough knowledge is present that the best estimate is known to be more likely than surrounding values.

3.4 Uncertainty Analysis

An uncertainty analysis was performed to compare the relative contributions of uncertainty in each of the primary input functions to uncertainty in the resulting EAD without a levee and with 50, 100 and 250-year (0.02, 0.01 and 0.004 exceedance

probability) levees. Uncertainty was varied in each input function according to the ranges defined in the Sensitivity to Uncertainty section. Uncertainty in the output was defined as the difference between the 0.25 exceedance probability and the 0.75 exceedance probability EAD (Goldman, pers. comm., 2000).

3.5 EAD Reduction

To examine the sensitivities of EAD reduction, with-project conditions were created. EAD reduction was examined for levees built to the 50-year, 100-year, and 250-year (0.02, 0.01 and 0.004 exceedance probability) levels. The same set of runs was done for the with-project conditions as for the without-project condition. The without-project EAD values were subtracted from the with-project EAD values to get EAD reduction, an estimate of benefits expected from the levee project.

3.6 Sensitivity Index

To analyze the sensitivity of EAD, EAD reduction, and their associated uncertainties to the above-described parameters on a consistent basis, a sensitivity index must be calculated. Simple sensitivity can be used as a first measure of uncertainty importance. Mathematically, simple sensitivity is defined as:

$U_s(x,y) = [\delta y/\delta x]_{xo}$

(Morgan and Henrion, 1990)

In terms of flood damage analysis, simple sensitivity can be written as:

$S_{x1}(x_1,x_2,x_3,y) = [\delta y/\delta x_1]x_{1o},x_{2o},x_{3o}$

where S = Simple Sensitivity of EAD to x_1

x_1 = Hydrologic Function; x_2 = Hydraulic Function; x_3 = Economic Function; y = EAD;

x_{1o} = Hydrologic Function at Base Case

x_{2o} = Hydraulic Function at Base Case

x_{3o} = Economic Function at Base Case.

This definition works well for parameters on the same scale. Simple sensitivity can be used to examine changes in input function sensitivity over a range of values. However, since the three primary relationships in flood damage analysis are on different scales, a normalized sensitivity must be used to compare the sensitivities between functions. The normalized sensitivity is also known as elasticity, which is essentially the percent change in output with the percent change in the uncertain parameter or input, defined as:

$U_E(x,y) = [\delta y/\delta x]_{xo} (x_o/y_o)$

(Morgan and Henrion, 1990)

In terms of flood damage analysis, this can be rewritten as:

$E_{x1}(x_1,x_2,x_3,y) = [\delta y/\delta x_1]x_{1o},x_{2o},x_{3o} (x_{1o}/y_o)$

where E = Elasticity of EAD to x_1

x_1 = Hydrologic Function; x_2 = Hydraulic Function; x_3 = Economic Function; y = EAD;

x_{1o} = Hydrologic Function at Base Case

x_{2o} = Hydraulic Function at Base Case

x_{3o} = Economic Function at Base Case; y_o = EAD at Base Case.

Simple sensitivity can be plotted for comparison of function parameter sensitivity over the range of values examined. Elasticity can be plotted for comparison of EAD sensitivity to each function. The same plots can be created for EAD reduction and the variance of EAD.

3.7 Case Studies

To test the results of the numerical experiments on the synthetic data sets, sensitivity to uncertainty was examined for two sample data sets. A data set from a typical large drainage basin on the Blue River, Missouri and a data set from a typical small drainage basin on the Chippewa River, Georgia were used for comparison. Both data sets had flow-exceedance probability curves that were well defined by an LPIII distribution and previously defined stage-flow and damage-stage curves.

Chapter 4

Results

The following graphs summarize the results of the Sensitivity and Uncertainty Analyses, as described in the Approach section. Elasticity (percent change in EAD or EAD Reduction divided by percent change in parameter value) was plotted against parameter value so the sensitivities could be compared on a unitless basis. All numerical results are included in Appendix A. A vertical line was drawn on each graph to delineate the base case value against which elasticity was measured. The sensitivity analysis results are presented according to function in the following order:

1. Flow-Exceedance Probability Mean - Figures 8 - 11
2. Flow-Exceedance Probability Standard Deviation - Figures 12 - 14
3. Flow-Exceedance Probability Skew – Figures 15 - 17
4. Stage-Flow Function Average Slope, "B" – Figures 18 - 21
5. Stage-Flow Function Y-Intercept, "C" – Figures 22 and 23
6. Damage-Stage Function Lower Bound of Damage-Producing Stages – Figures 24 and 25
7. Damage-Stage Function Upper Bound of Damage-Producing Stages – Figures 26-28
8. Damage-Stage Function Inflection Points, A and B – Figure 29 - 32

4.1 Flow-Exceedance Probability Sensitivity Analysis

The sensitivity of EAD and EAD reduction to the three moments of the flow-exceedance probability function was examined by computing elasticity relative to the large and small base cases. The elasticity of EAD and EAD reduction to mean flow for the large basin was the highest for the first few thousand cubic feet per second below the base case, and declined as the flow decreased. The small basin showed a steadier decline in elasticity as flow decreased. The elasticity of EAD and EAD reduction to mean flow was higher for the small basin than for the large basin over nearly the entire flow range examined. For both basins, EAD reduction with a 50-year (0.02 exceedance probability) levee was more sensitive to mean flow than EAD reduction with the larger levees. As the levee size increases, the elasticity of EAD reduction approaches that of EAD without a levee. As levee size increases, the damage prevented approaches the total damage expected without a project.

While the elasticity of EAD and EAD reduction with a 50-year (0.02 exceedance probability) levee increased steadily with mean flow, the elasticity of EAD reduction with 100 and 250-year (0.01 and 0.004 exceedance probability) levees decreased temporarily at a mean flow of around 24,000 cfs. This occurs because the average steepness of the damage-producing part of the stage-damage curve decreases when mean flow reaches 24,000 cfs with a 100 or 250-year (0.01 or 0.004 exceedance probability) levee. As the mean flow is increased to 24,500 cfs, the average steepness of the damage-producing part of the stage-damage curve does not change compared to

what it was at a mean of 24,000 cfs, so the elasticity increases again due to the increase in flow. The results are summarized in Figures 8 and 9.

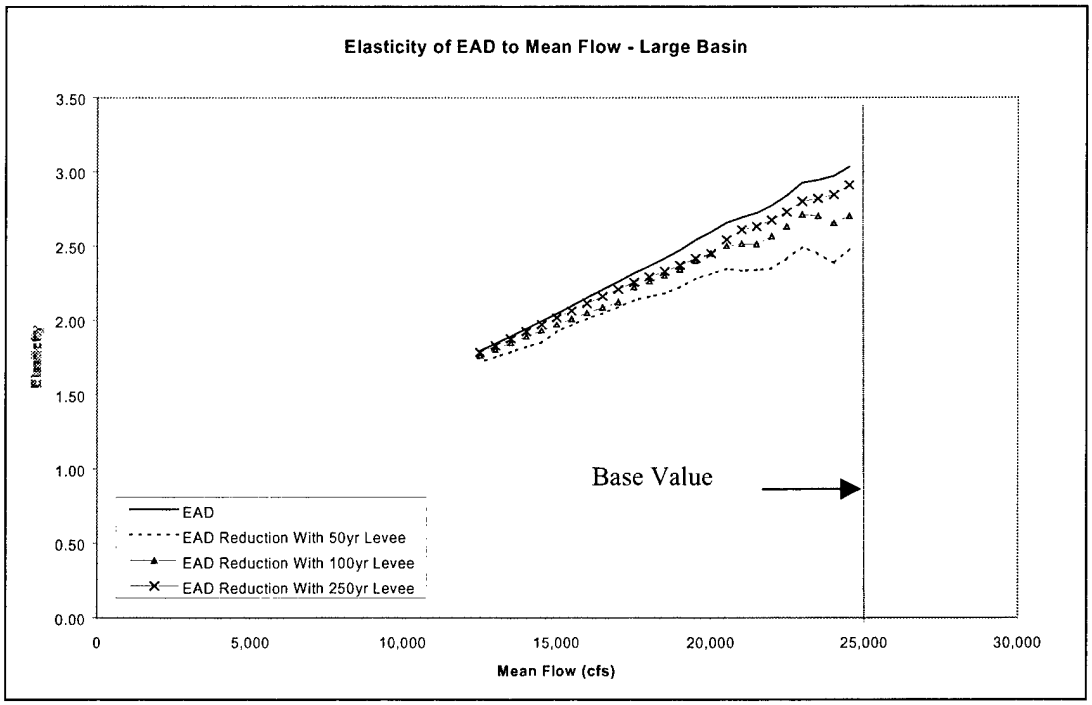

Figure 8. Elasticity of EAD and EAD Reduction with Mean Flow, Large Basin

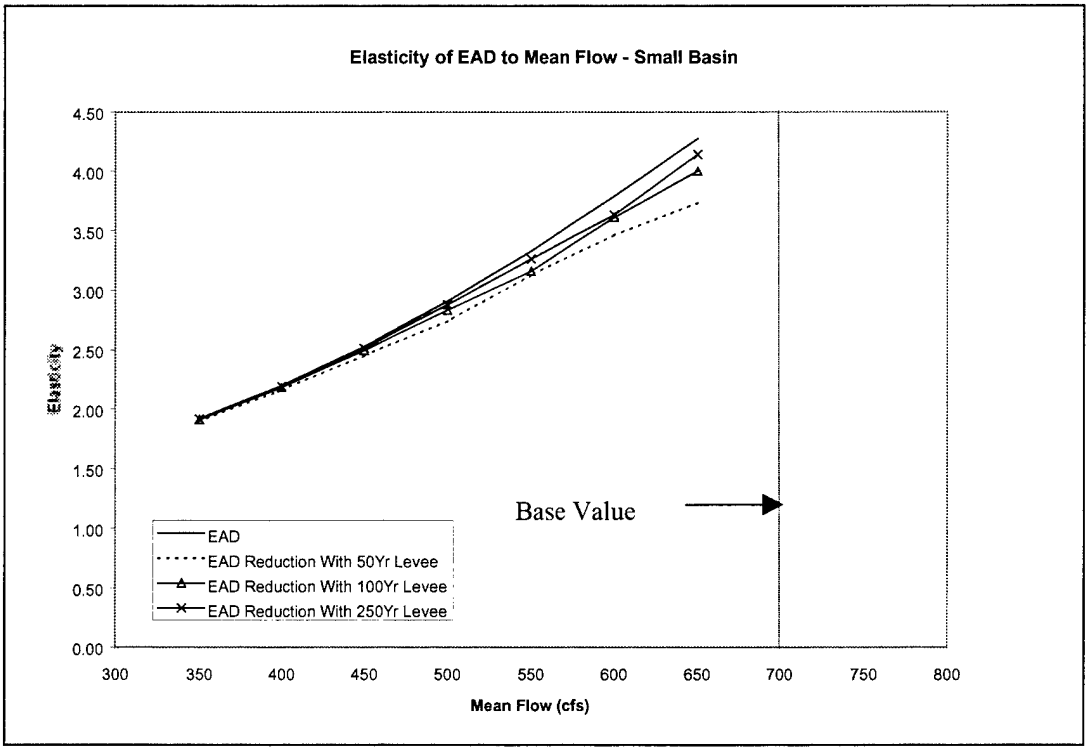

Figure 9. Elasticity of EAD and EAD Reduction with Mean Flow, Small Basin

The change in mean flow is typically propagated through the EAD calculation through a series of steps. If new data were obtained that decreased the best estimate of the mean flow, the entire flow-exceedance probability curve would be lowered, thus changing the flow range required for the stage-flow curve to be integrated with the flow-exceedance probability curve. To isolate the mean for sensitivity analysis, only the range of the stage-flow curve was changed to match the range of flows for each mean flow. However, examination of data sets from across the United States showed that mean flow can be correlated with the average slope of the rating curve, as shown in Figures 5a and 5b. Changing the average slope of the rating curve according to this correlation with mean flow changes the behavior of EAD, EAD reduction and elasticity.

The mean flow – stage-flow curve slope correlation shows that streams with lower mean flows tend to have steeper rating curves. A steeper rating curve tends to increase EAD, while a lower mean flow will tend to decrease EAD. A set of model runs was completed to demonstrate the interaction of these tendencies. The resulting elasticity changes can be seen in Figures 10 and 11. When the rating curve becomes steep enough, the effect of steepening the curve dominates the EAD elasticity. When the steepness of the rating curve dominates EAD elasticity, the elasticity can decrease. This is most evident in the small basin (Figures 9 and 11). When the rating curve is flat enough the mean flow dominates the EAD elasticity, increasing its values at the higher flows. This is most evident in the large basin (Figures 8 and 10).

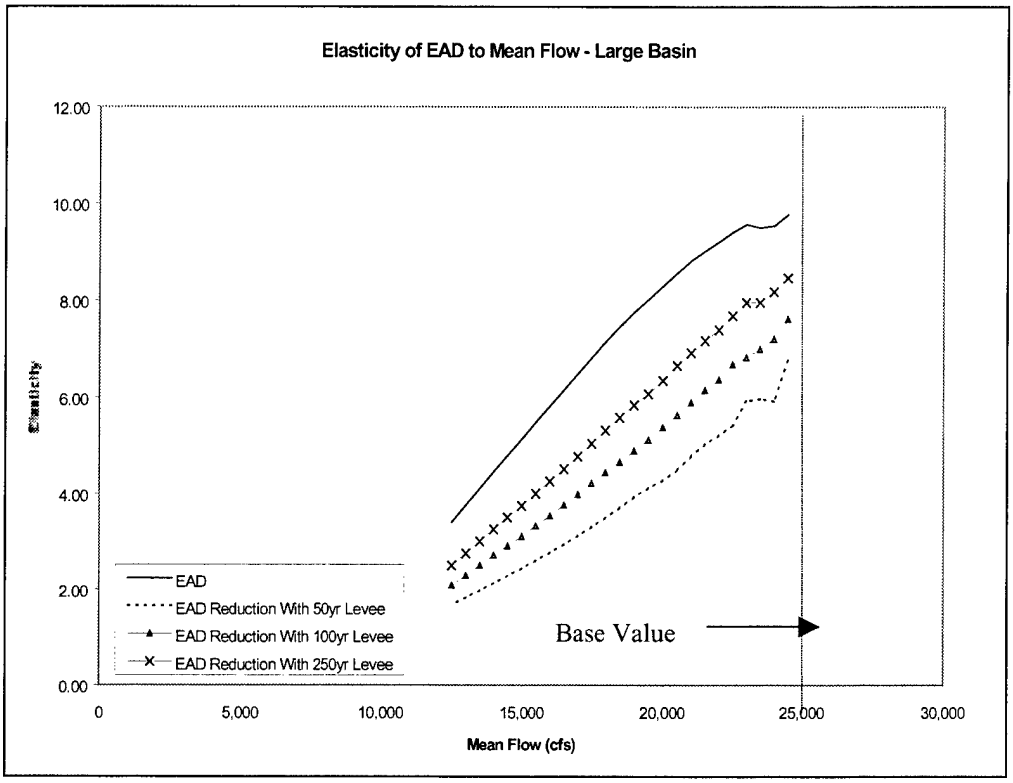

Figure 10. Elasticity of EAD and EAD Reduction to Mean Flow with Adjusted Rating Curve, Large Basin

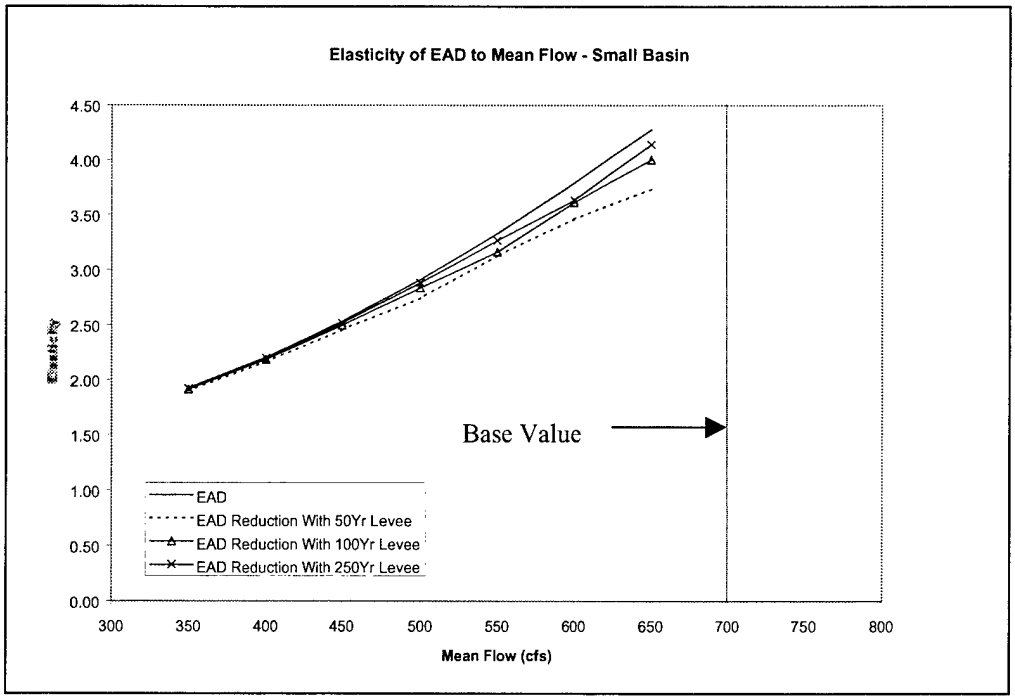

Figure 11. Elasticity of EAD and EAD Reduction to Mean Flow with Adjusted Rating Curve, Small Basin

The elasticity of EAD and EAD reduction with standard deviation of flow was the highest for the first few cubic feet per second above the base case, and decreased steadily for both the large and small basins. EAD and EAD reduction for all levee sizes were more elastic for changes in standard deviation of the flow-exceedance probability function than for the mean of the flow exceedance probability function over the ranges examined. As with the mean flow, EAD and EAD reduction were more elastic for the large basin than for the small basin. Also, the trend of decreasing elasticity with increasing levee size was opposite of the previous results. These results are summarized in Figures 12 and 13.

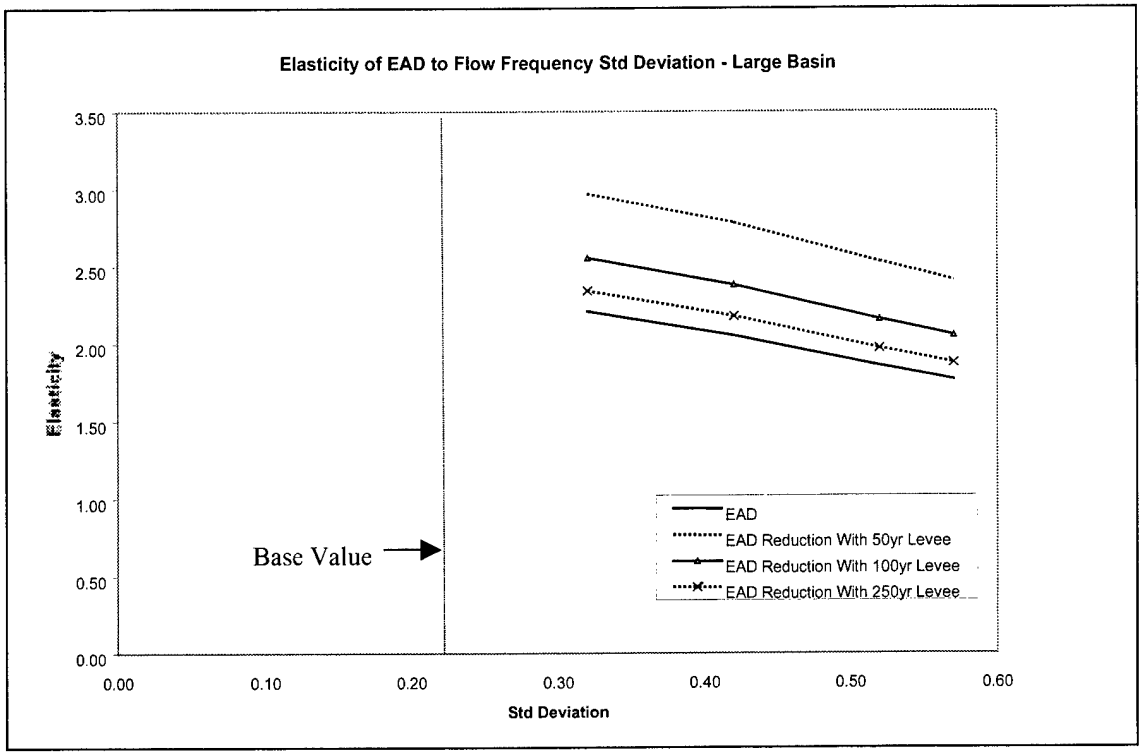

Figure 12. Elasticity of EAD and EAD Reduction with Standard Deviation of Flow, Large Basin

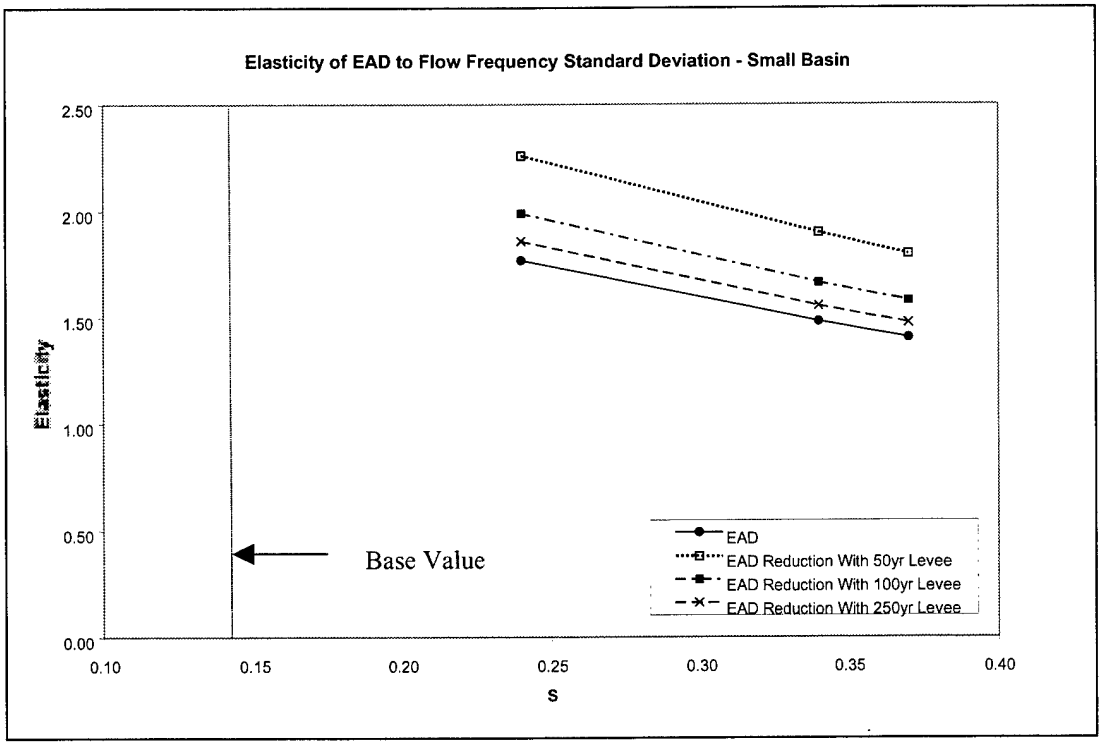

Figure 13. Elasticity of EAD and EAD Reduction with Standard Deviation of Flow, Small Basin

Changes in the standard deviation of the flow-exceedance probability function are propagated differently than changes in the mean flow. As the standard deviation is increased, the slope of the flow-exceedance probability function increases. This creates two opposing trends, as illustrated in Figure 14.

1. Less frequent (high flow) events are larger.
2. More frequent events are smaller.

Construction of a levee eliminates damages from the more frequent decreased lower flows, but the damages from the increased higher flows remain. The net effect of increasing the standard deviation of flow is to increase EAD and EAD reduction, but decrease elasticity.

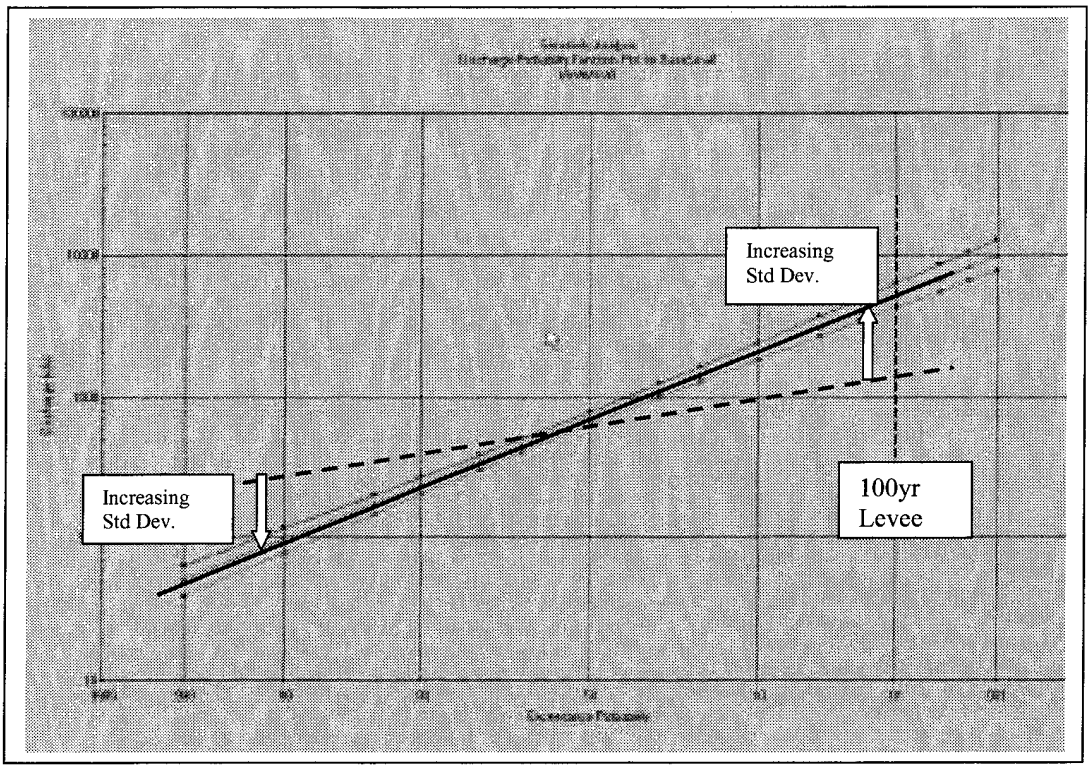

Figure 14. The Effects of Increasing Standard Deviation of the Flow-Exceedance Probability Function

The elasticity of EAD and EAD reduction with the flow-exceedance probability skew follows the same behavior for the large basin as for the small basin. Positive skew values increase the magnitude of the highest probability and lowest probability flows, while decreasing the magnitude of the middle probability flows to a lesser degree. Negative skew values decrease both of these magnitudes, while increasing the magnitude of the middle probability flows to a lesser degree. These trends can be seen in Figure 15.

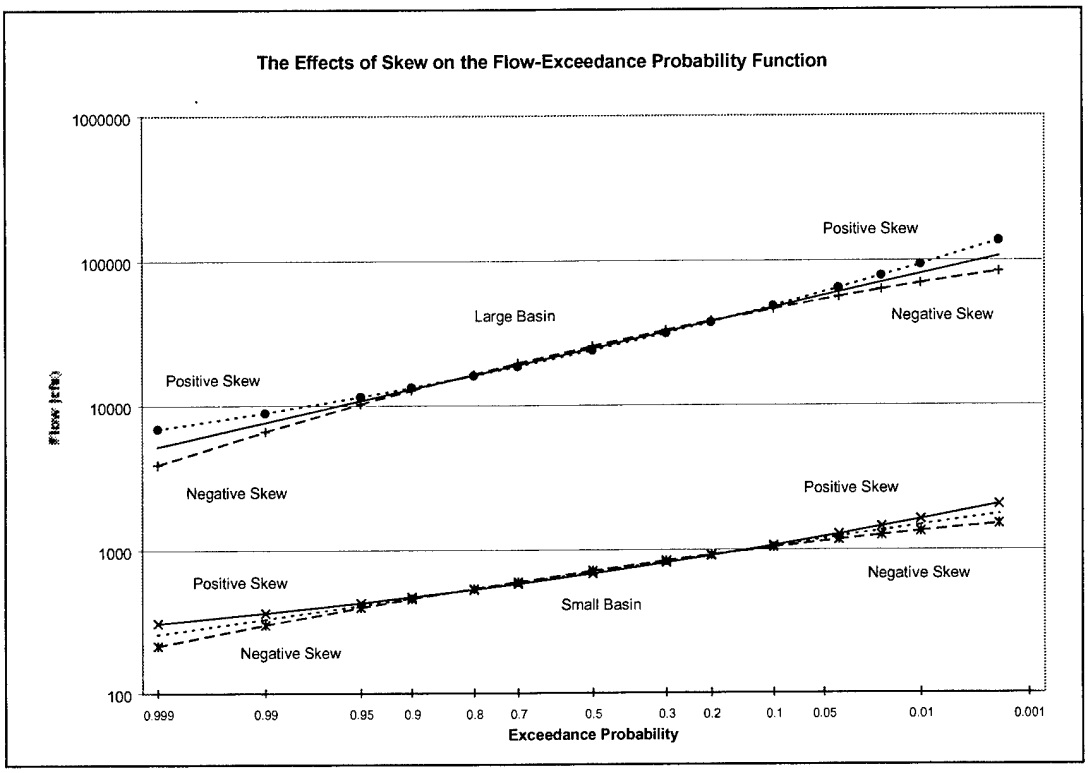

Figure 15. The Effects of Skew on the Flow-Exceedance Probability Function

Compared to the mean and standard deviation of the flow-exceedance probability function, elasticity decreases very slowly with increasing skew for the small basin, and even more slowly for the large basin. For skew, elasticity was measured against a base value of 0.1 because elasticity cannot be computed against a value of zero. There are ranges of negative skew over which the elasticities of EAD and EAD reduction remain approximately constant or increase very slightly. This occurs when increasing the higher flows can no longer affect EAD because there is already 100% damage. In this case, EAD is affected slightly by the change in the middle probability flows in the opposite direction. When the skew coefficient was small enough to shift the flow-exceedance probability curve below the 100-year (0.01 exceedance probability) and 250-year (0.004 exceedance probability) levee heights that were sized at zero skew the EAD became approximately zero. Since this is unrealistic, the flow-exceedance probability curve is not extended beyond the 0.001 exceedance probability. Over all skew ranges examined, both the large and small basins were significantly less sensitive to skew than to mean or standard deviation of the flow-exceedance probability function. The results are summarized in Figures 16 and 17.

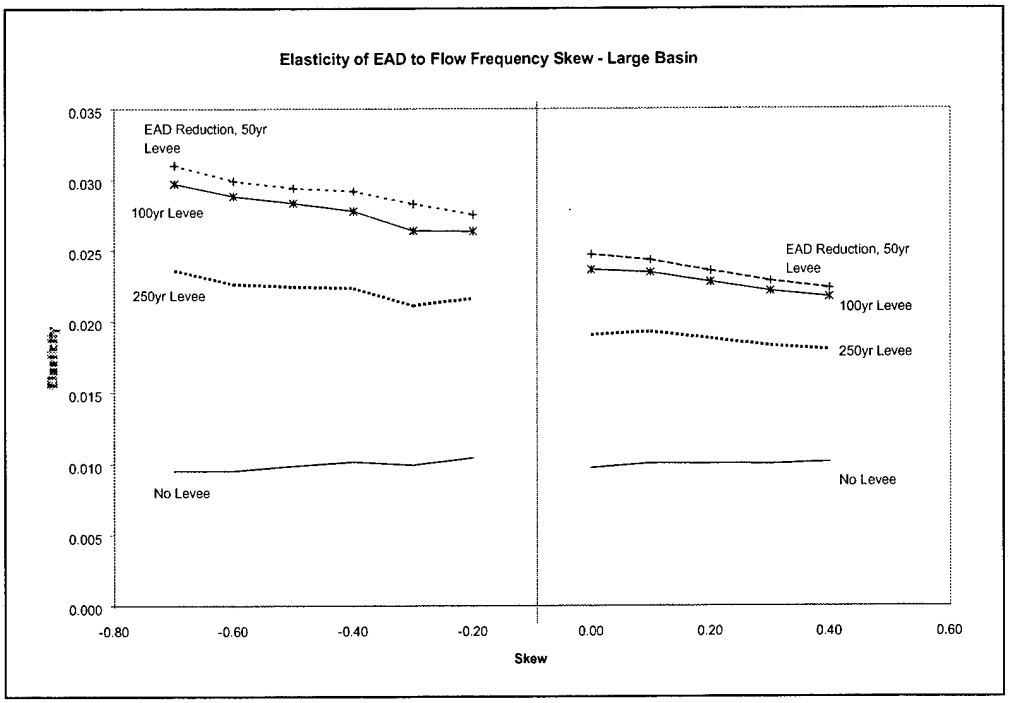

Figure 16. Elasticity of EAD and EAD Reduction with Skew of Flow-Exceedance Probability Function, Large Basin

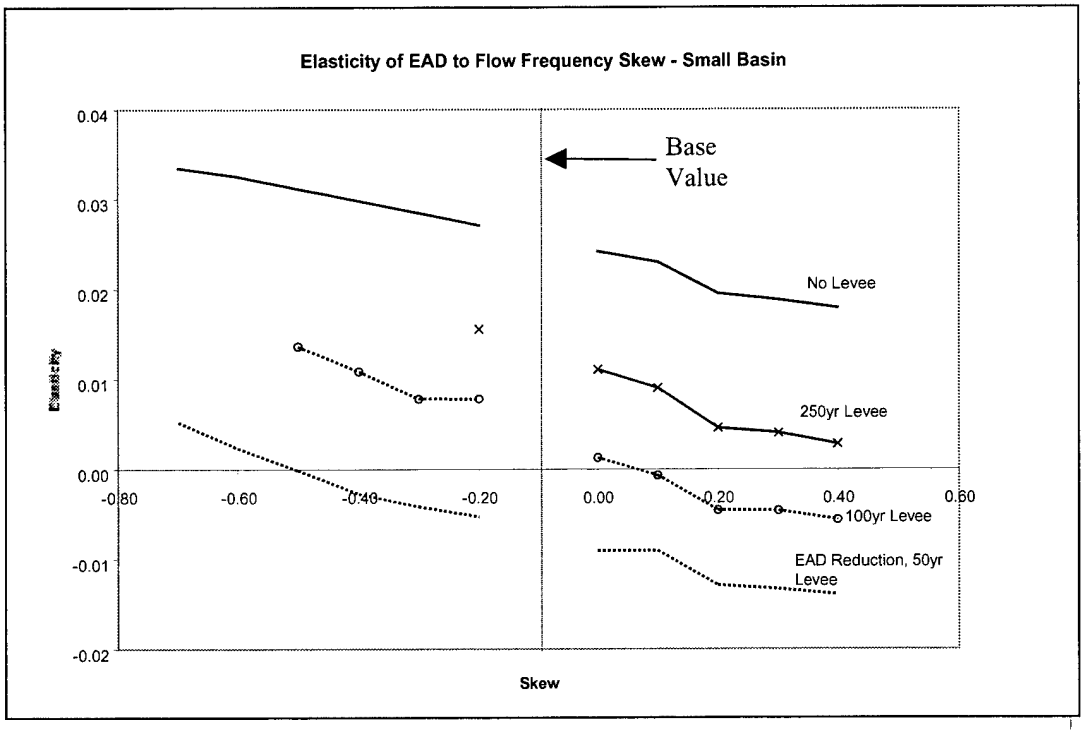

Figure 17. Elasticity of EAD and EAD Reduction with Skew of Flow-Exceedance Probability Function, Small Basin

4.2 Stage-Flow Sensitivity Analysis

The average slope of the stage-flow function is defined by the "b" parameter in the general quadratic equation used to define the stage-flow curve, as discussed in Chapter 3:

$S = aQ^2 + bQ + c$ where S = Stage (ft) and Q = Flow (cfs).

The elasticity of EAD and EAD reduction with the average slope of the stage-flow function is greatest for steeper functions. It follows that the elasticity is greatest for smaller basins. In general, as the average slope increases, EAD increases quickly. As the slope of the stage-flow function increases, higher stages become associated with the same flows, and thus higher damages until damages reach a maximum limit. The elasticity of EAD increases initially as slope increases above the base case, then decreases as EAD approaches total damage. The elasticity of EAD reduction decreases steadily with increasing slope above the base case. As the average slope becomes flatter than the base case, elasticity of EAD reduction quickly approaches that of EAD. The results are summarized in Figures 18 and 19. The range in stage-flow function slopes examined can be seen in Figures 20 and 21.

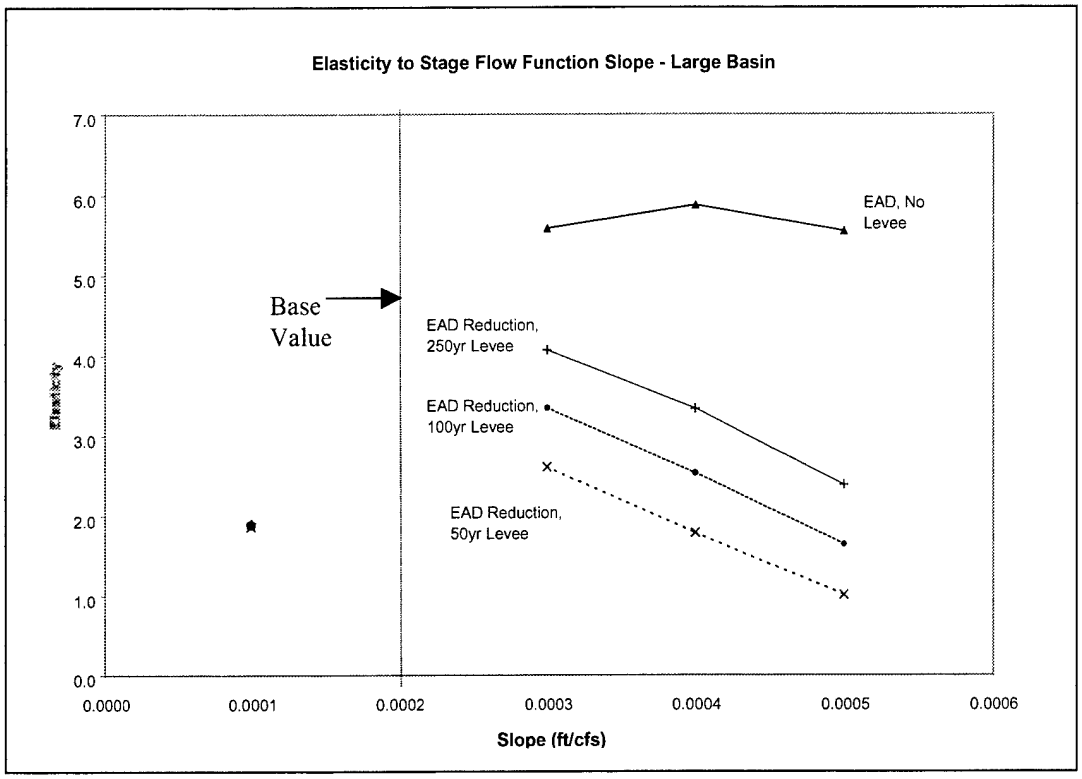

Figure 18. Elasticity of EAD and EAD Reduction with Stage-Flow Function Average Slope, Large Basin

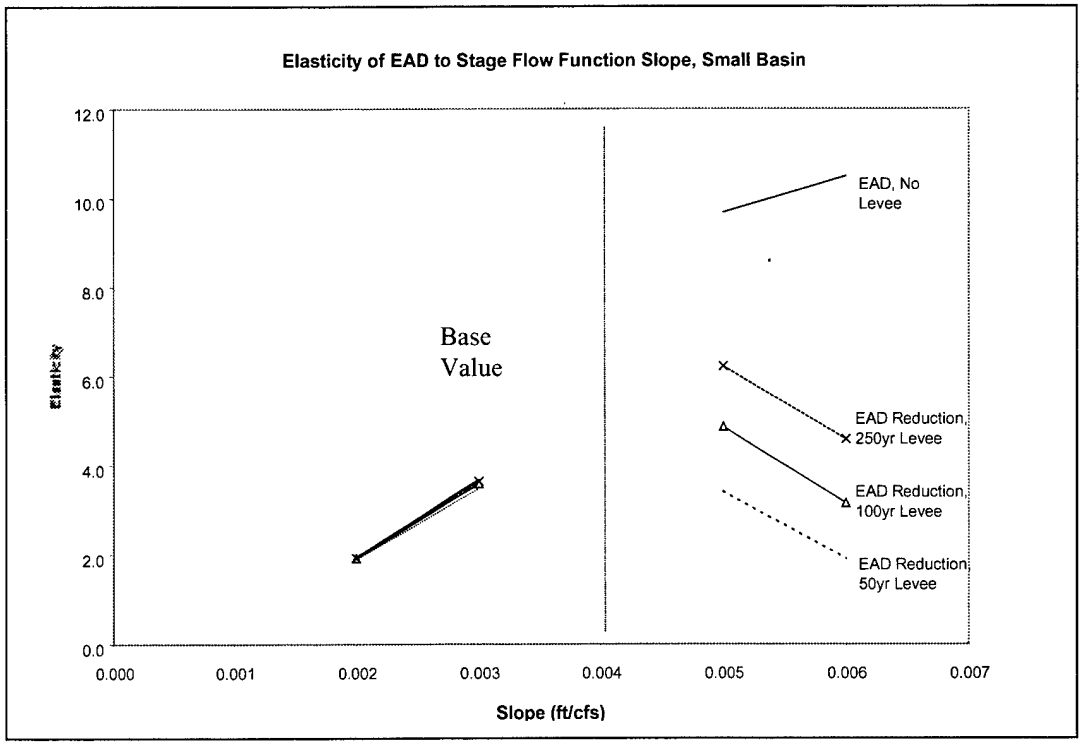

Figure 19. Elasticity of EAD and EAD Reduction with Stage-Flow Function Average Slope, Small Basin

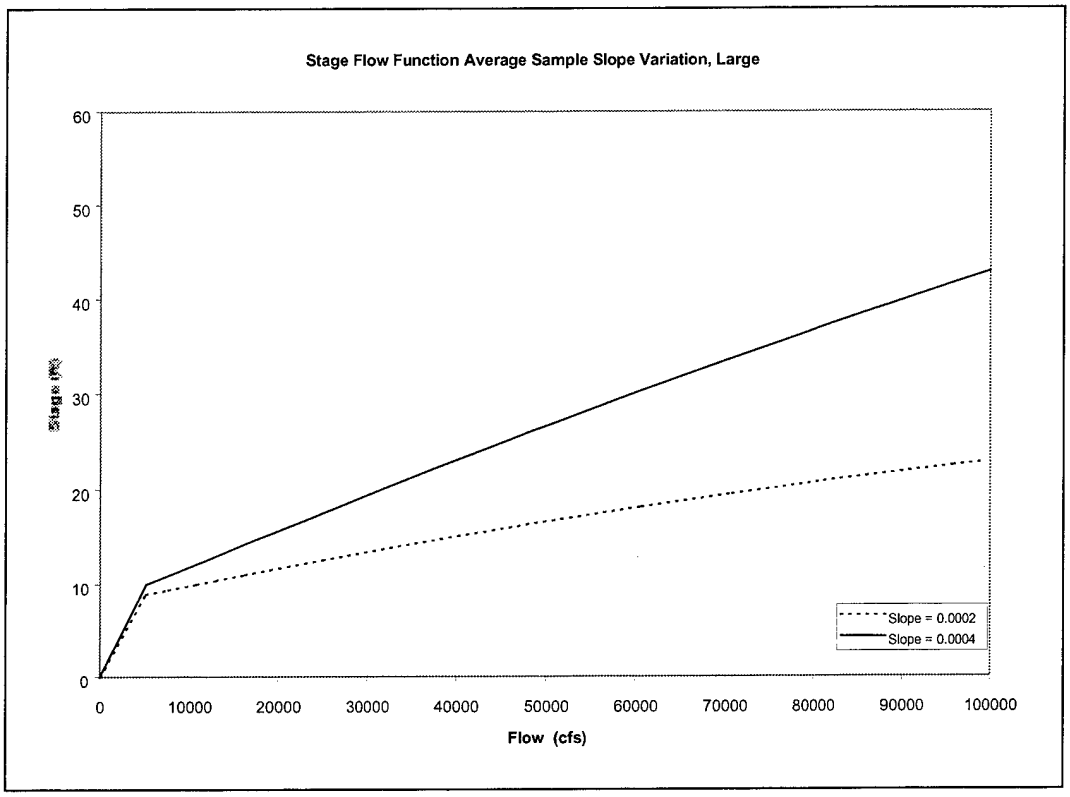

Figure 20. Variation in Stage-Flow Function Slope, Large Basin

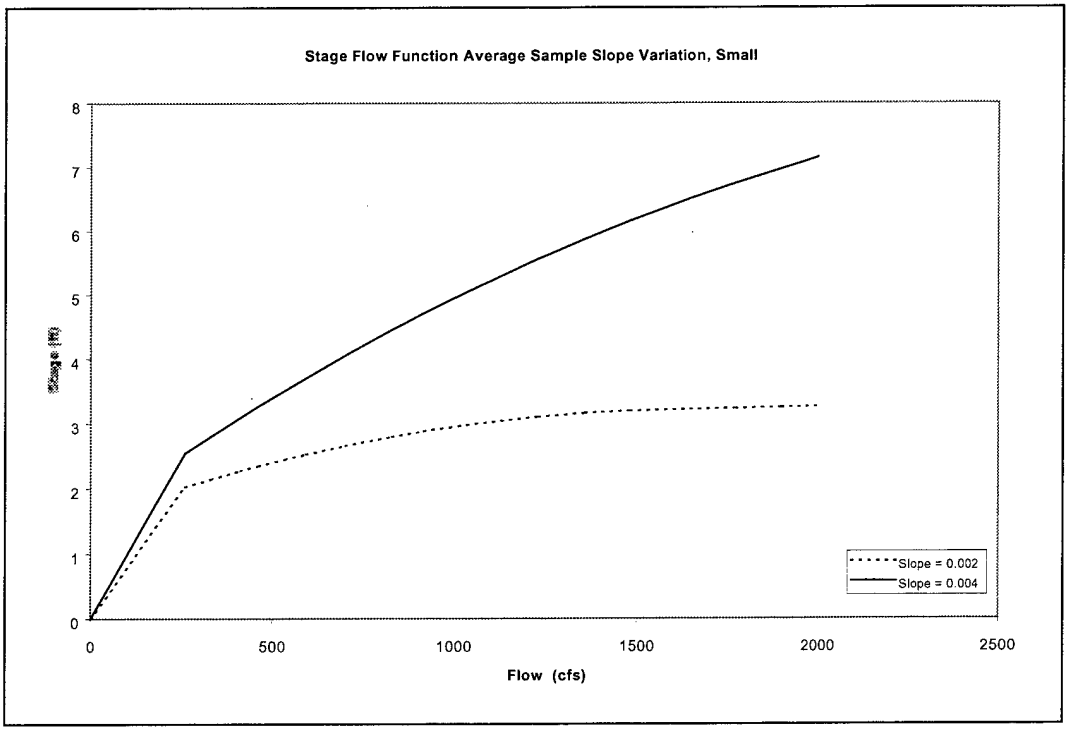

Figure 21. Variation in Stage-Flow Function Slope, Small Basin

The "C" parameter in the synthetic stage-flow functions represents the y-intercept of the curve as given in the general quadratic equation:

$S = aQ^2 + bQ + c$ where S = Stage (ft) and Q = Flow (cfs).

Increasing "C" increases EAD and EAD reduction. For the large basin, elasticity increased with increasing "C". For the small basin, elasticity increased with increasing "C", but began to decrease as the maximum damage was approached. In general, the elasticity of EAD and EAD reduction to the "C" parameter was similar for each basin size. The results are shown in Figures 22 and 23. The change in "C" value is propagated the same way as the change in function slope. Increasing "C" increases the stage for each flow, thereby increasing the damages until a maximum limit is reached.

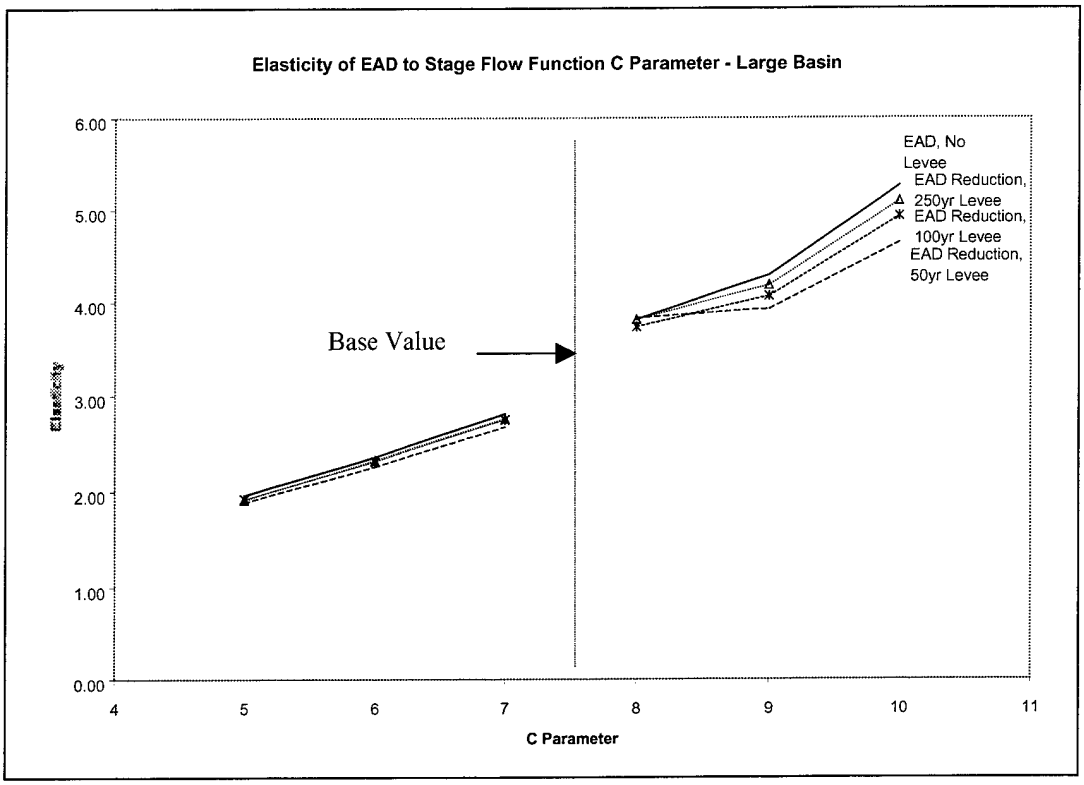

Figure 22. Elasticity of EAD and EAD Reduction with Stage-Flow Function "C" Parameter, Large Basin

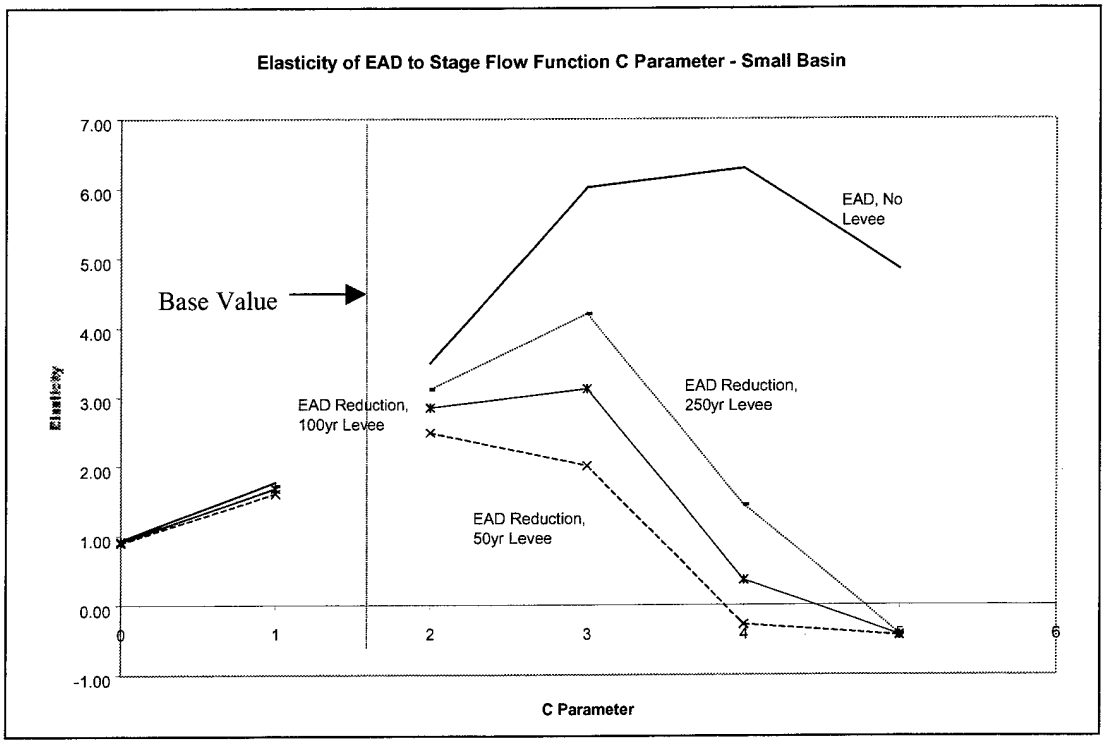

Figure 23. Elasticity of EAD and EAD Reduction with Stage-Flow Function "C" Parameter, Small Basin

4.3 Damage-Stage Sensitivity Analysis

Elasticity was calculated for a range of lower bounds of the damage-producing stages. The lower bound is the stage at which damage begins. As the lower bound of damage-producing stages was increased, EAD and EAD reduction decreased. Elasticity also decreased steadily with an increasing lower bound for both the large and small basins. As the lower bound increased, the levees prevented a greater proportion of damages from occurring. The elasticity of EAD and EAD reduction was more than twice as high for the small basin as for the large basin for the values examined. Increasing the lower bound effectively eliminates damage from the most common events, while changing the less common events relatively little. The results are summarized in Figures 24 and 25.

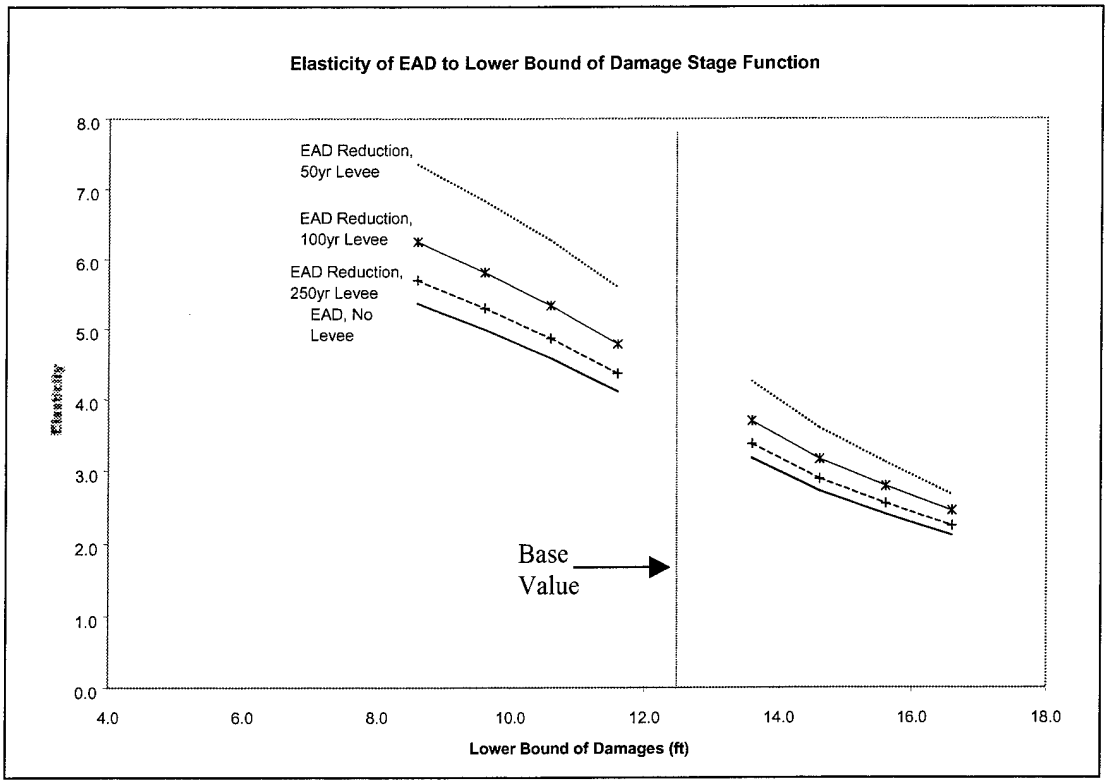

Figure 24. Elasticity of EAD and EAD Reduction with Damage-Stage Function Lower Bound of Damages, Large Basin

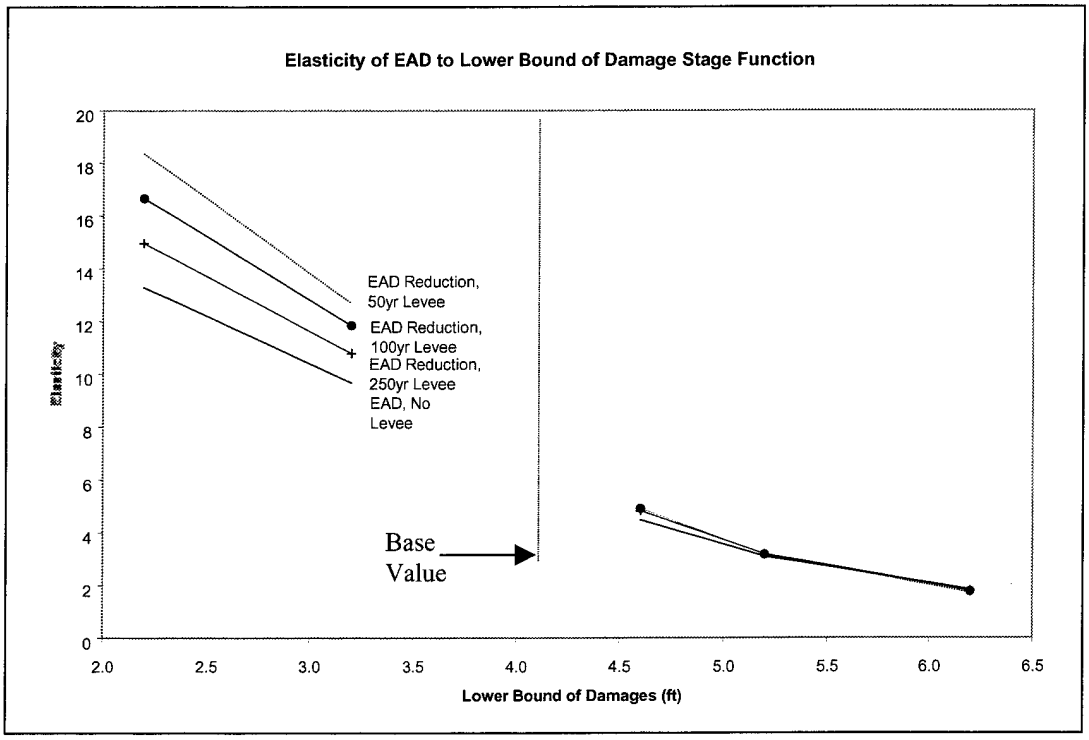

Figure 25. Elasticity of EAD and EAD Reduction with Damage-Stage Function Lower Bound of Damages, Small Basin

Elasticity was calculated for each basin with different upper bound stages. The upper bound stage is the stage above which maximum damage occurs. As the upper bound was increased, EAD and EAD reduction decreased. Elasticity also decreased steadily for the large basin, but at different rates depending on how high the levee was for the small basin (See Figures 27 and 28). Considering that damage is assumed to only occur above the top of levee stage, the average relative steepness of the damage-producing part of the curve varies with different levee stages (See Figure 26). For instance, without a levee the curve for the upper bound equal to 6.2 is steeper than the curve with 7.2. However, when a 50-year (0.02 exceedance probability) levee is added, the damage-producing part of the curve for the upper bound equal to 6.2 becomes flatter than the curve with 7.2. When a 100-year (0.01 exceedance probability) levee is added, the curve with 6.2 remains flatter, but when a 250-year (0.004 exceedance probability) levee is added it becomes steeper again. These changes are mirrored in the elasticity curve for the small basin (Figure 28).

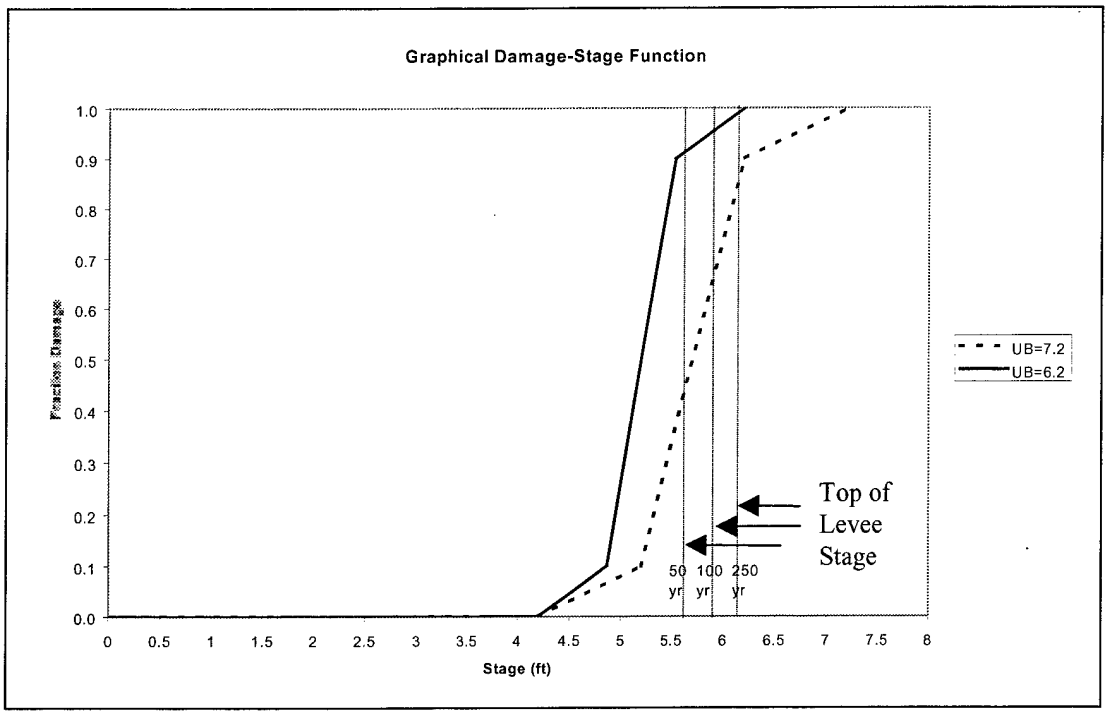

Figure 26. Variation of Damage-Stage Curve Upper Bound

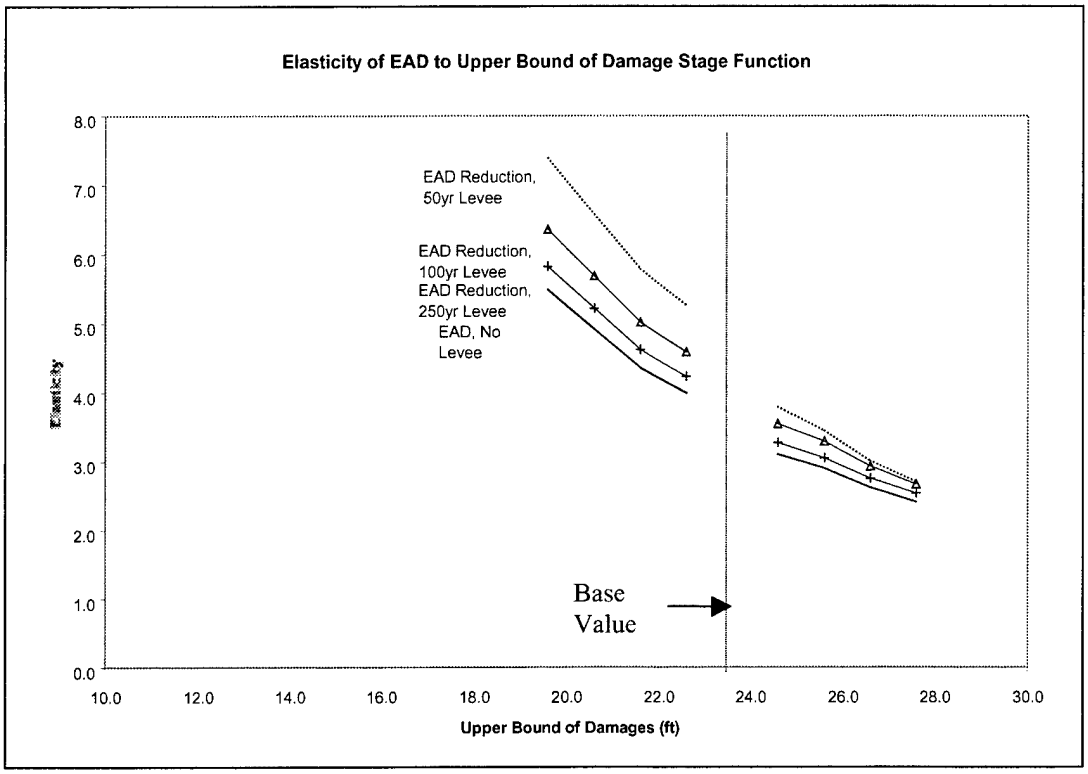

Figure 27. Elasticity of EAD and EAD Reduction with Damage-Stage Function Upper Bound of Damage, Large Basin

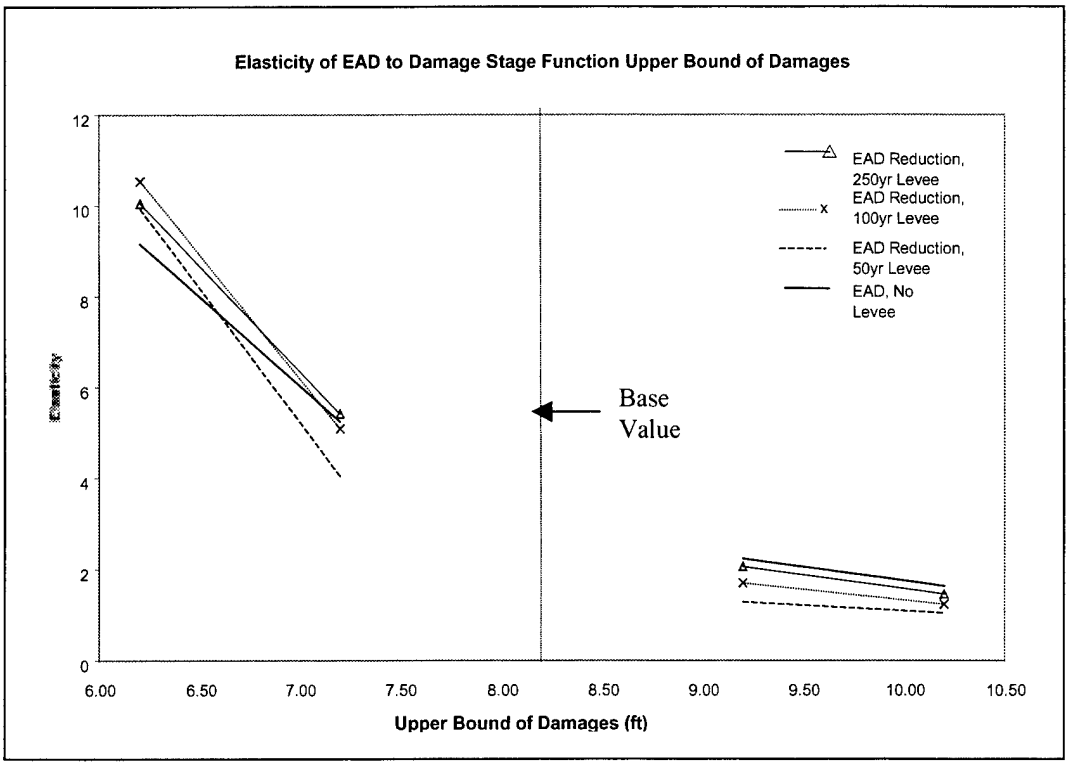

Figure 28. Elasticity of EAD and EAD Reduction with Damage-Stage Function Upper Bound of Damage, Small Basin

Elasticity was calculated for variation in each inflection point of the damage-stage function independently. Since only three values were examined for the first (lower) and second (higher) inflection points apiece, the elasticity values were graphed as a maximum and minimum value. In general, as the first inflection point "A" increased, EAD decreased for both the large and small basins. As the second inflection point "B" increased, EAD decreased for both the large and small basins. EAD had a higher maximum elasticity for the small basin than for the large basin for both inflection points, but a lower minimum elasticity for both inflection points.

EAD and EAD reduction had a higher elasticity in both basins to the first inflection point than to the second. The propagation of changing an inflection point in the stage damage function is similar to changing the lower bound of damage-producing stage. In general, the larger levee scenarios had a lower maximum elasticity of EAD reduction, but a higher minimum elasticity. This can be seen in Figures 29 – 32.

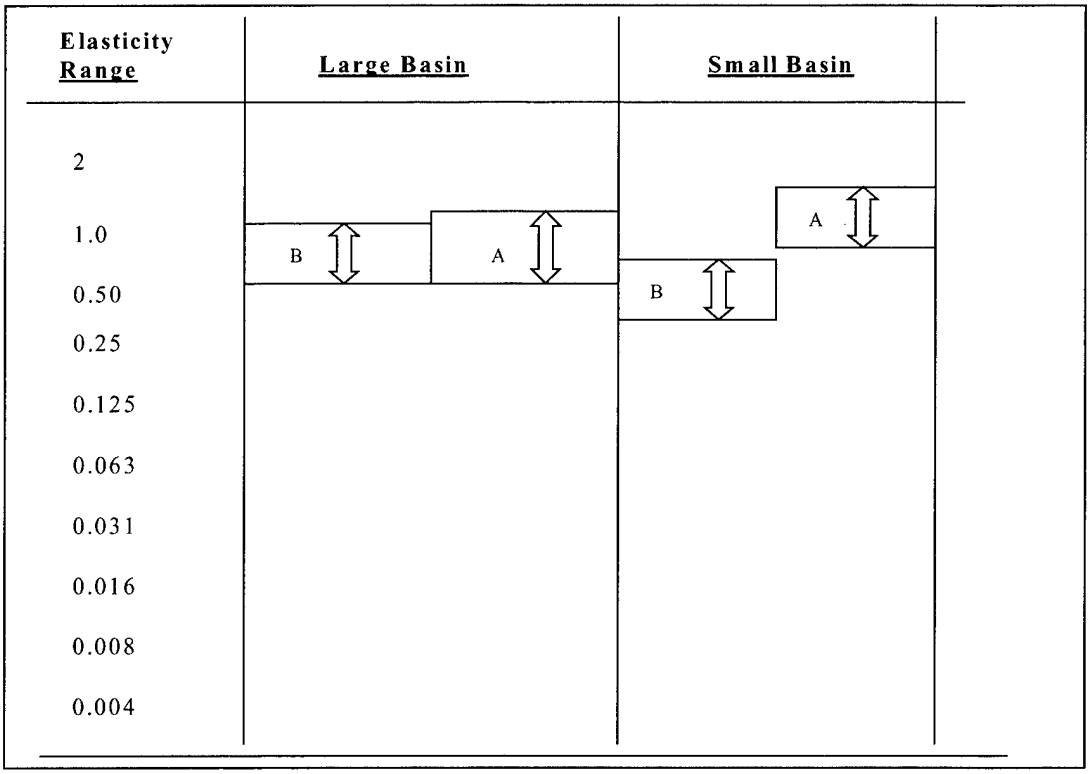

Figure 29. Elasticity of EAD with Damage-Stage Function Inflection Point Locations for Large and Small Basins

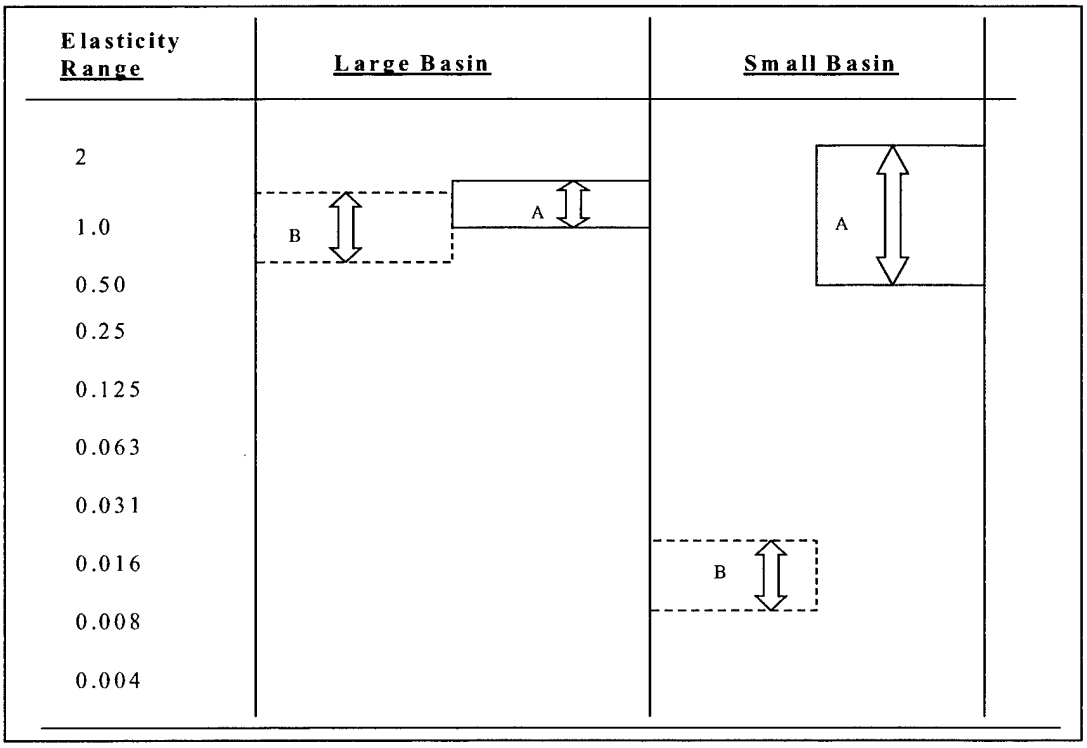

Figure 30. Elasticity of 50-yr Levee EAD Reduction with Damage-Stage Function Inflection Point Locations for Large and Small Basins

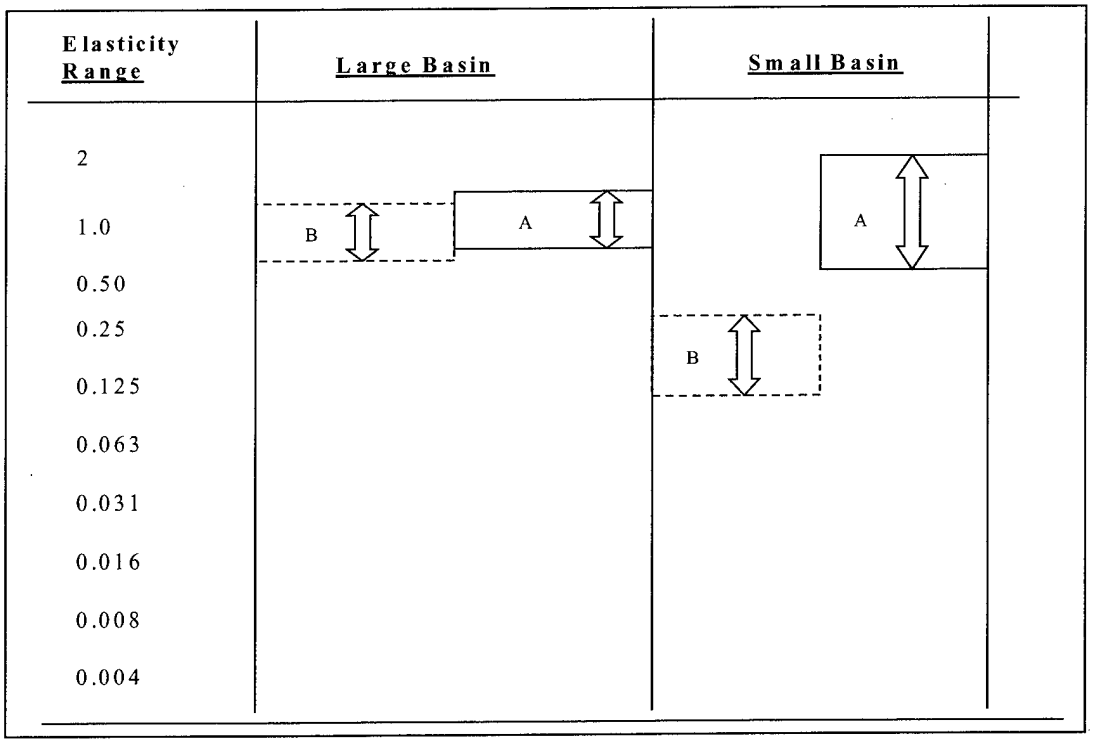

Figure 31. Elasticity of 100-yr Levee EAD Reduction with Damage-Stage Function Inflection Point Locations for Large and Small Basins

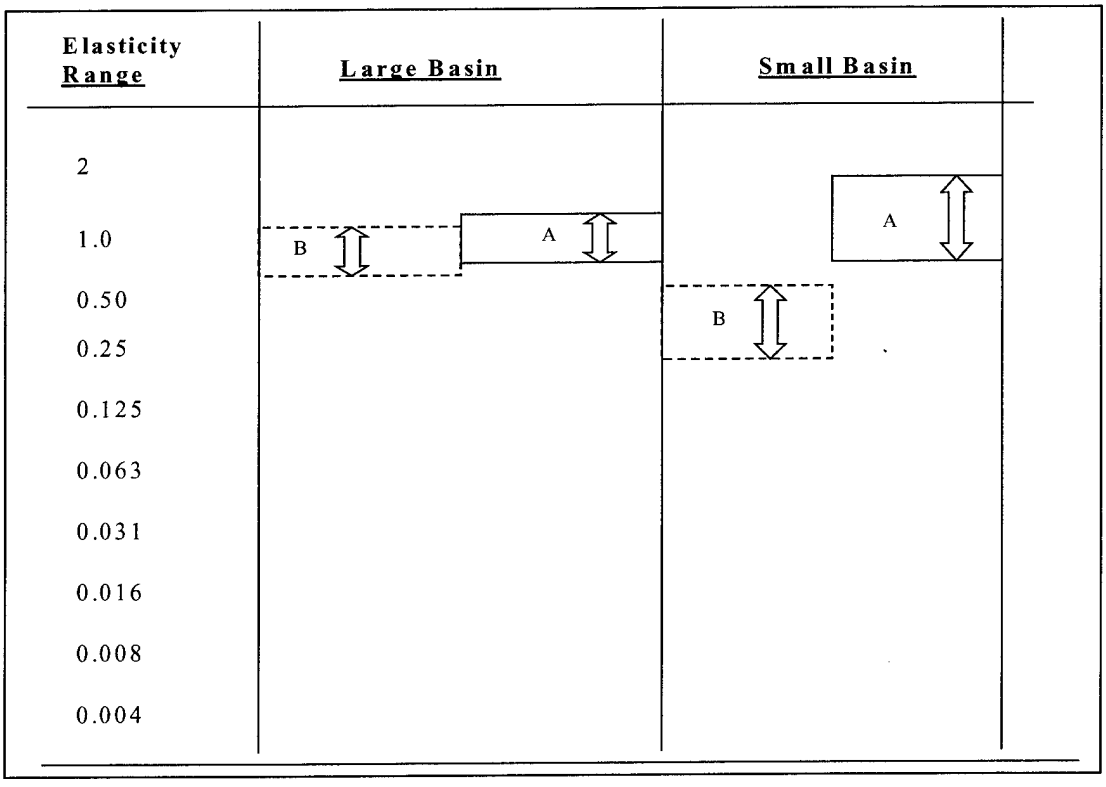

Figure 32. Elasticity of 250-yr Levee EAD Reduction with Damage-Stage Function Inflection Point Locations for Large and Small Basins

4.4 Sensitivity to Uncertainty

Based on the results of HEC-FDA for a range of equivalent record lengths, elasticity was calculated for each record length to compare results on a unitless basis. Each individual model run output is included in Appendix A. Elasticity values are summarized in Figure 33 for the small/steep and large/flat basins. Likewise, elasticity was calculated for each standard deviation of error about the flow-stage curve, with each individual model run output included in Appendix A. Elasticity values for flow-stage uncertainty are summarized in Figure 34. Since the mean EAD is not sensitive to stage-damage uncertainty (Lindquist, 1995), no plot was produced for its elasticity. However, model runs were still completed to verify this result and are included in Appendix A.

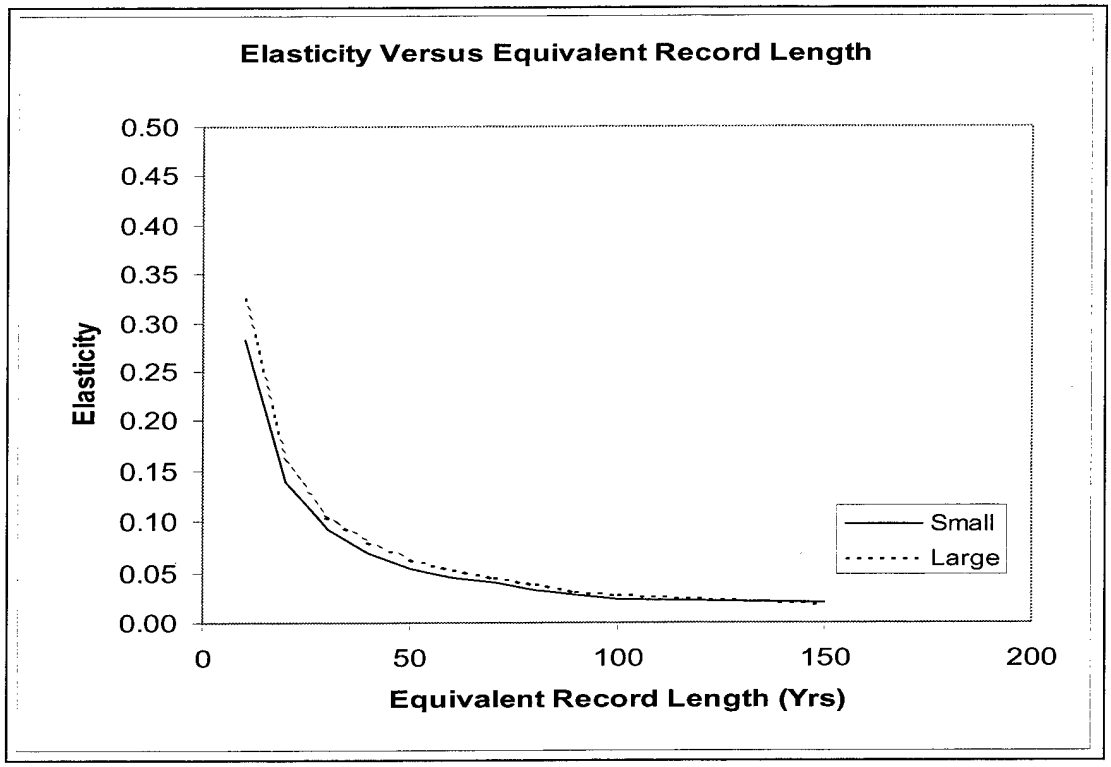

Figure 33. EAD Elasticity to Equivalent Record Length

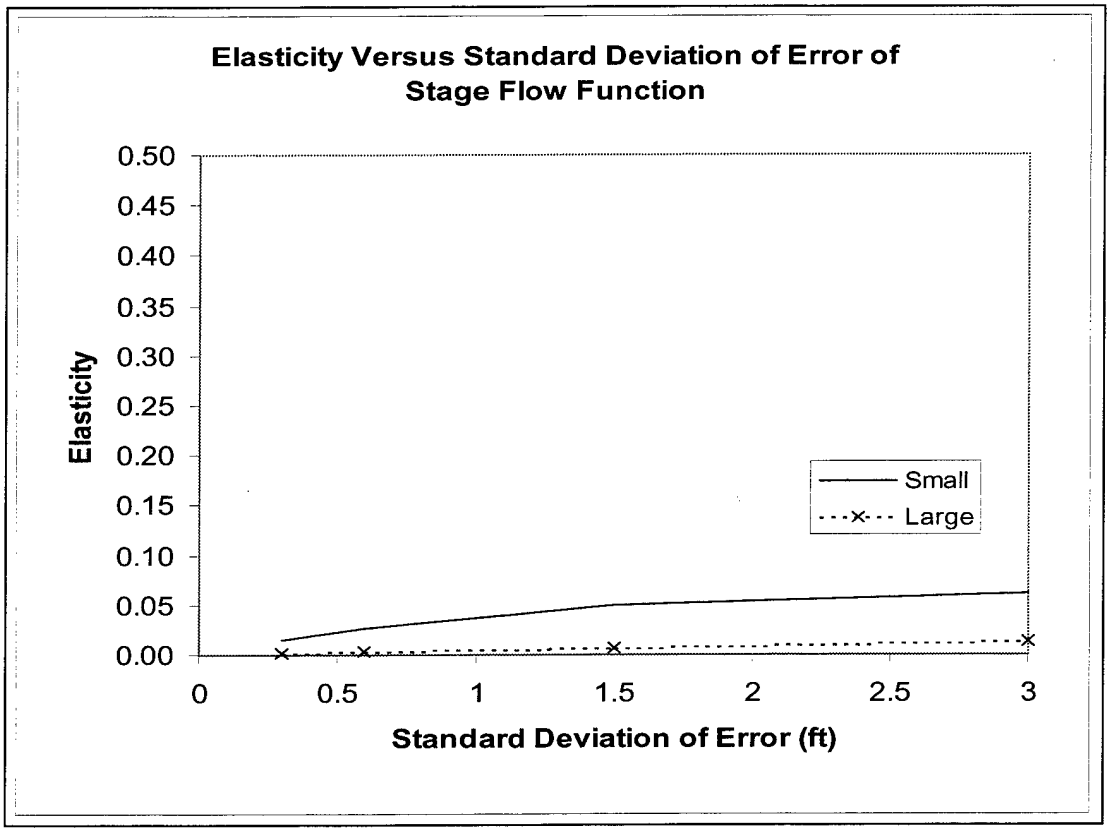

Figure 34. EAD Elasticity to Stage-Flow Error

Over the range of values examined, EAD had the highest elasticity with flow record length. This was always the case for the large basin, and usually the case for the small basin. EAD had the highest elasticity with stage-flow standard deviation of error for the small basin when the record length was long and the standard deviation of stage-flow error was large.

The maximum and minimum elasticity of EAD to each function uncertainty was calculated from the range of results. These values can be compared for the large and small basins in Figures 35.

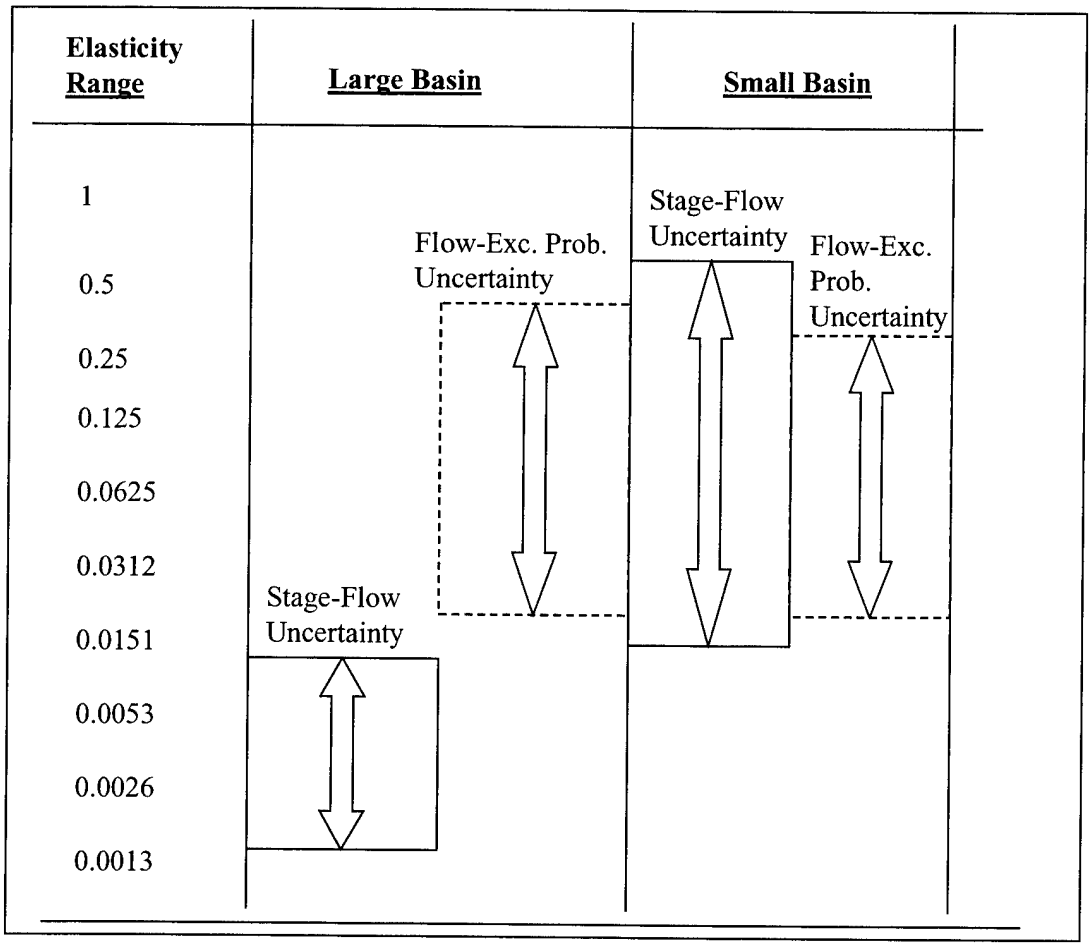

Figure 35. Uncertainty Elasticity Comparison –EAD

Based on the results from varying record length with 50, 100 and 250-year (0.02, 0.01 and 0.004 exceedance probability) levees, elasticity to equivalent record length was calculated for EAD reduction, the difference between EAD without and with each levee. Elasticity of EAD reduction to equivalent record length was plotted for each levee in each synthetic basin in Figure 36. Elasticity was also computed for the standard deviation of error of the stage-flow function, and plotted in Figure 37. The elasticity of EAD reduction generally decreases with increasing record length, but increases slightly in some cases depending on the slope of the damage-stage curve. The changing of the average slope of the damage-stage curve can be seen in Figure 26.

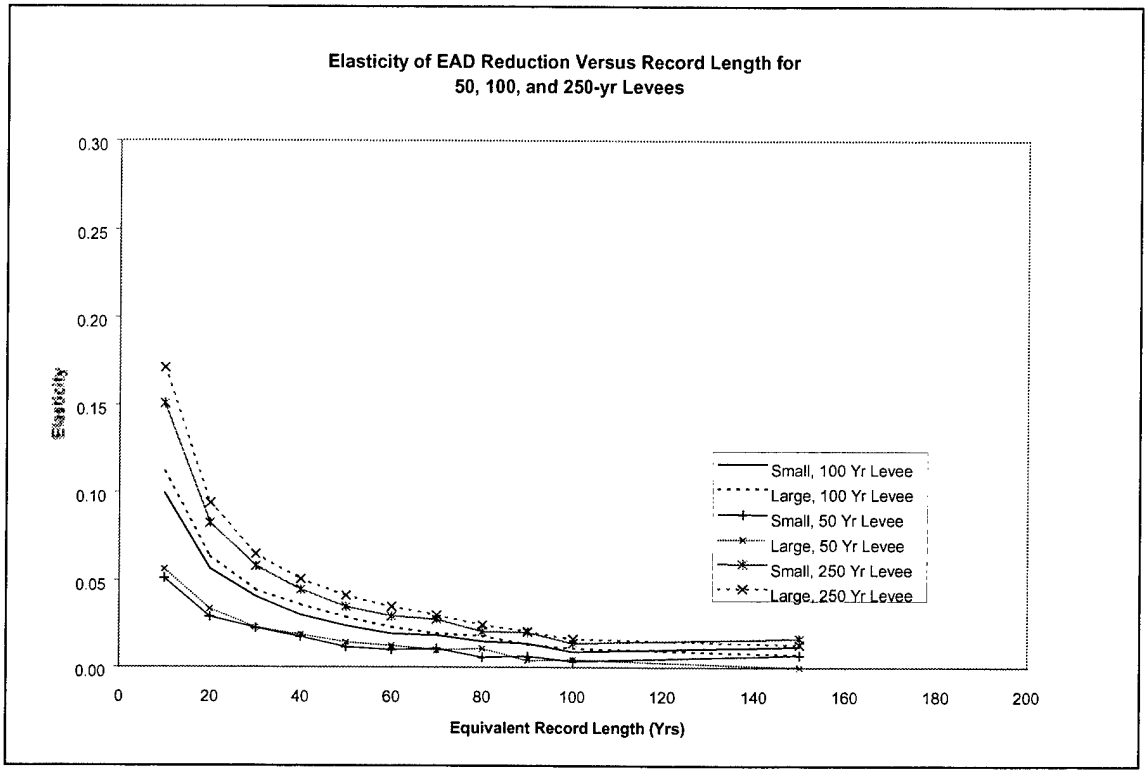

Figure 36. EAD Reduction Elasticity to Equivalent Record Length

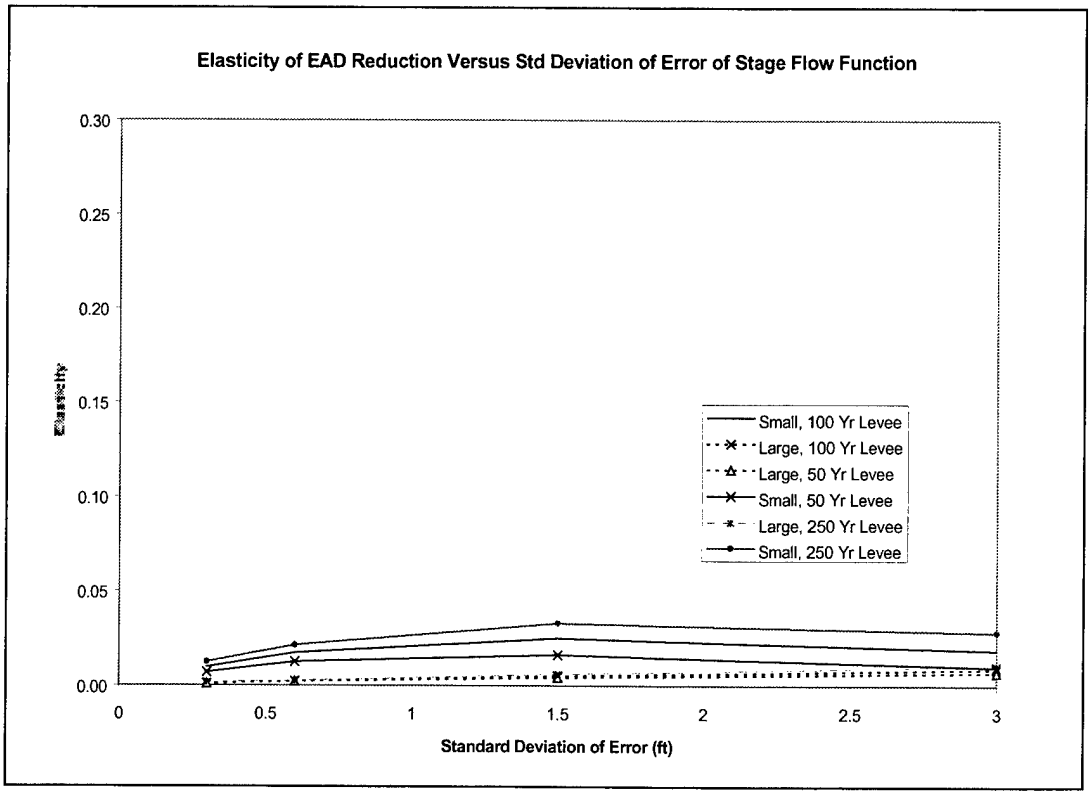

Figure 37. EAD Reduction Elasticity to Flow-Stage Standard Deviation of Error

The behavior of the elasticity of EAD reduction was similar to that of EAD, but on a smaller scale. EAD reduction had the largest elasticity with respect to equivalent record length over the entire range for the large basin, and over most of the range for the small basin. However, for long record lengths and large standard deviations of error for the flow stage function, EAD reduction was more elastic with respect to stage-flow function uncertainty. The ranges of elasticity of EAD reduction for the 50, 100 and 250-year (0.02, 0.01 and 0.004 exceedance probability) levees are summarized in Figures 38 through 40.

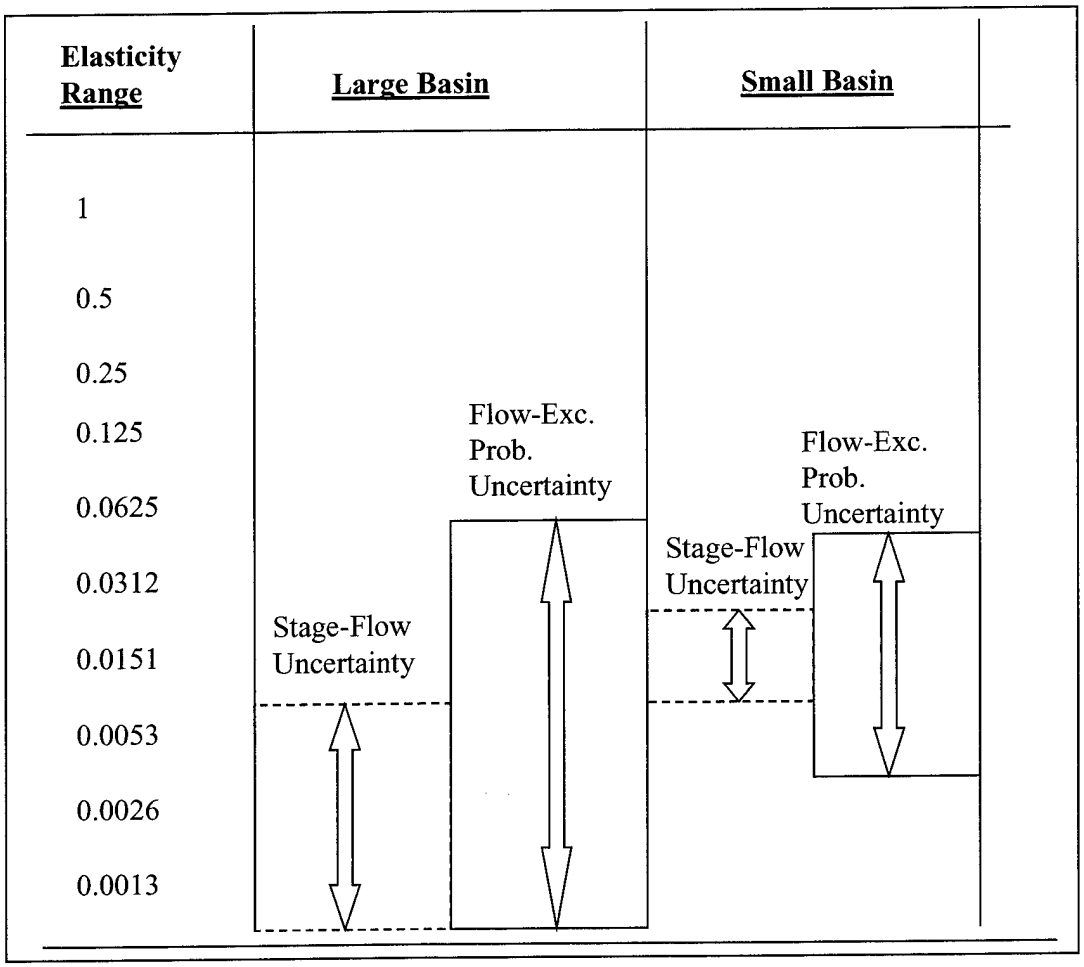

Figure 38. Uncertainty Elasticity Comparison –EAD Reduction with 50-Year (0.02 Exceedance Probability) Levee

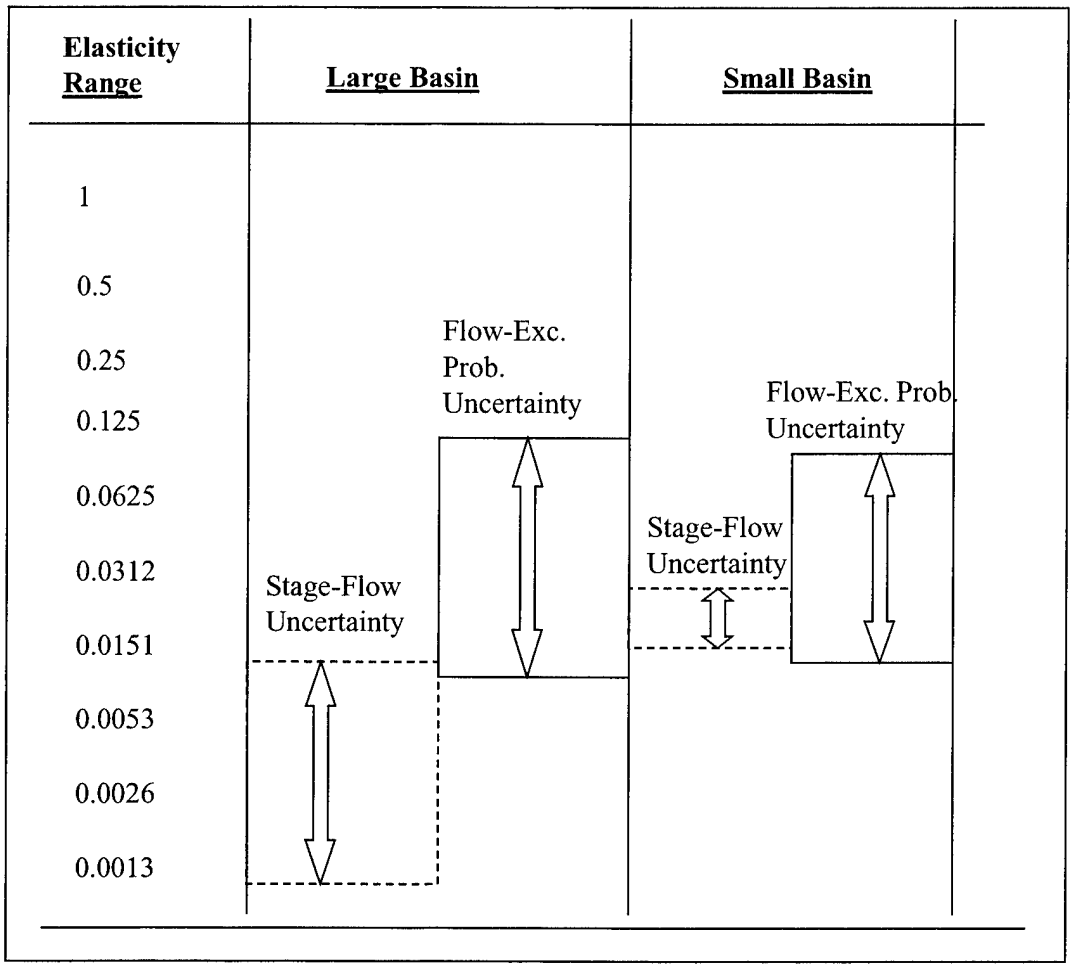

Figure 39. Uncertainty Elasticity Comparison –EAD Reduction with 100-Year (0.01 Exceedance Probability) Levee

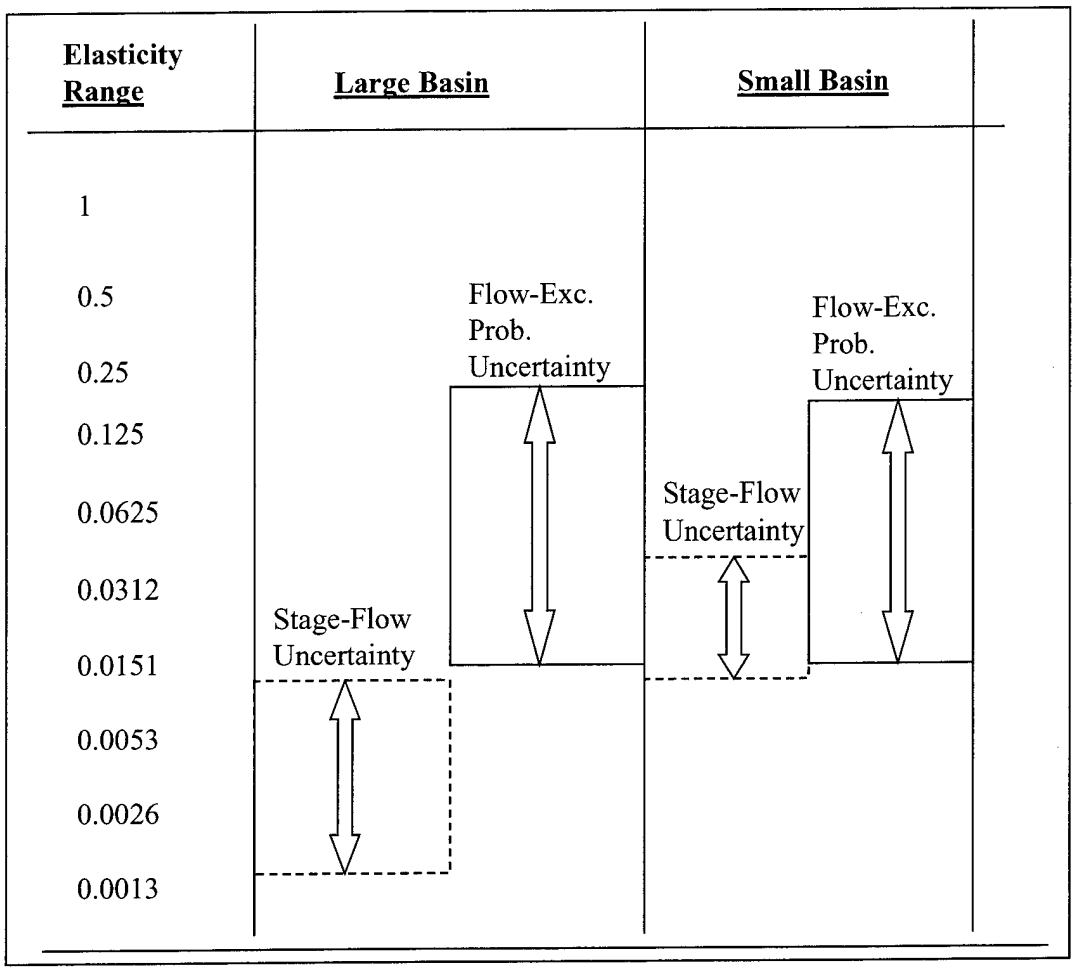

Figure 40. Uncertainty Elasticity Comparison –EAD Reduction with 250-Year (0.004 Exceedance Probability) Levee

4.5 Uncertainty Analysis

An uncertainty analysis was completed to examine the contribution of uncertainty in each primary function to uncertainty in EAD for no levee and with 50, 100 and 250-year (0.02, 0.01 and 0.004 exceedance probability) levees. To provide a basis for comparison, uncertainty in EAD was defined as the difference between the 0.25 exceedance and 0.75 exceedance quantiles in the output distribution. The numerical results are included in Appendix A and graphed in Figures 41, 42, and 43 for the flow-exceedance probability, stage-flow and damage-stage functions, respectively.

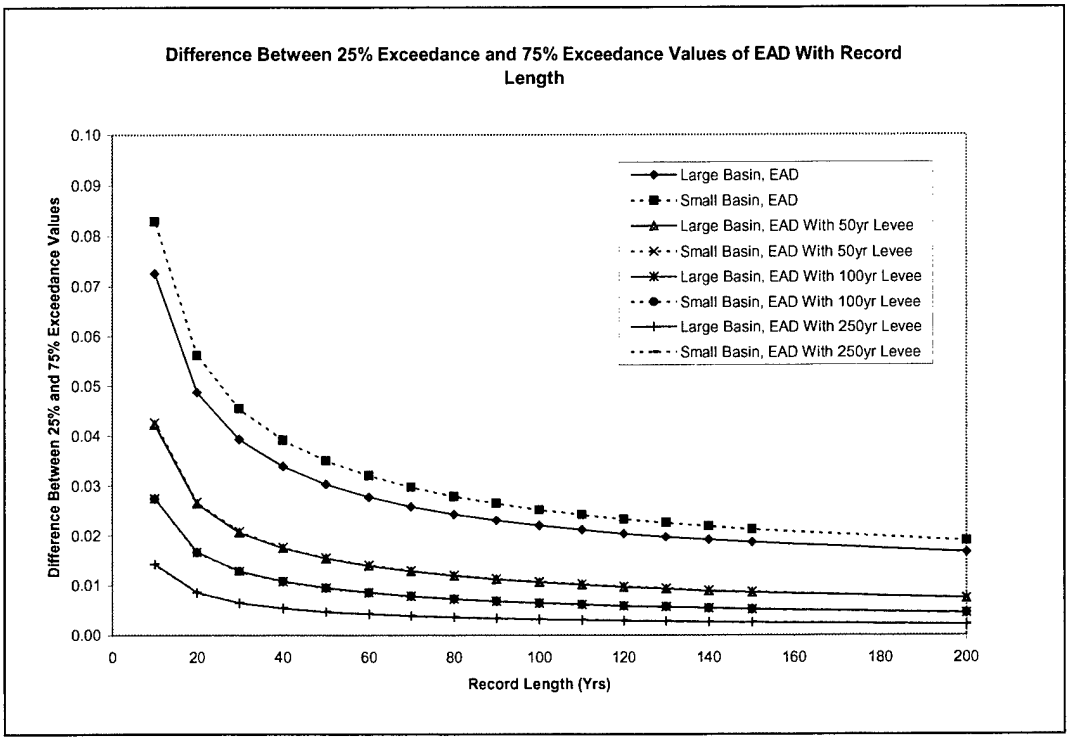

Figure 41. Flow-Exceedance Probability Uncertainty Analysis

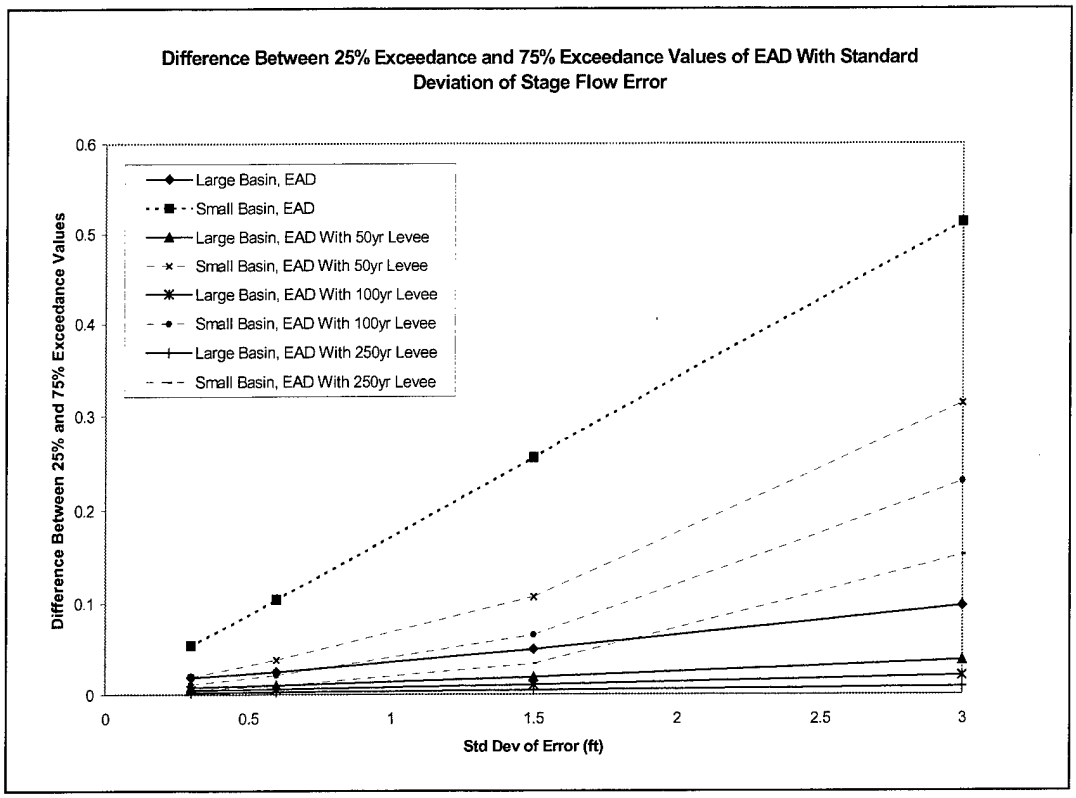

Figure 42. Stage-Flow Uncertainty Analysis

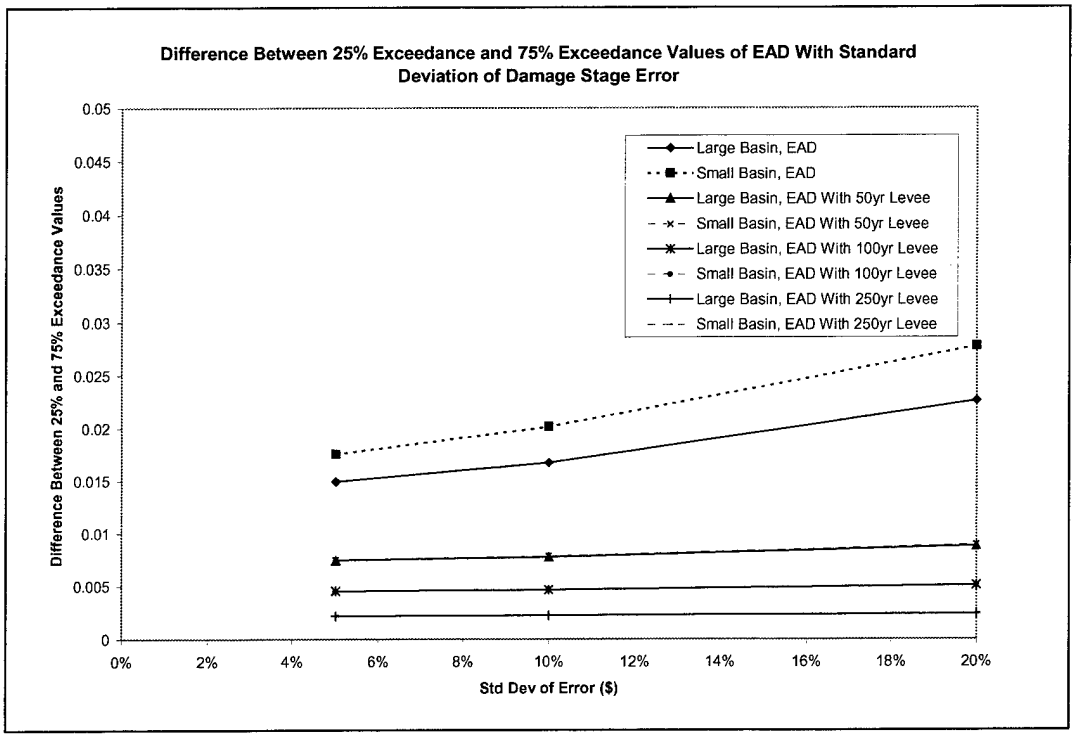

Figure 43. Damage-Stage Uncertainty Analysis

The relative contribution of uncertainty in each primary function to uncertainty in EAD depends upon in which ranges the individual uncertainties lie. The relative contribution of uncertainty increases as record length decreases or the standard deviation of error of the stage-flow function or damage-stage function increases. In general, the uncertainty contribution for the small basin is larger than the uncertainty contribution for the large basin with the same input uncertainty. This difference is smaller for the flow-exceedance probability and damage-stage functions and more pronounced for the stage-flow function. The contribution of each function to uncertainty in EAD decreases with increasing levee size. The uncertainty contribution from the flow-exceedance probability function begins to level off for record lengths greater than about 60 years without a levee, and greater than about 50 years with a levee. The uncertainty contribution from the stage-flow function increases more steadily with standard deviation of error, as does the contribution from the damage-stage function.

Over most of the ranges examined, stage-flow uncertainty appears to have the greatest contribution to uncertainty in EAD for the small basin, whereas flow-exceedance probability uncertainty appears to have the greatest contribution to uncertainty in EAD for the large basin. While the relative strength of each contribution can be inferred by isolating uncertainties in this manner, the interaction between uncertainties is not as easily defined.

4.6 Case Study Results

The results of the Chippewa River and Blue River case studies verified the results of the sensitivity to uncertainty experiments conducted on the synthetic basins. Slight differences in elasticity can be attributed mainly to the different shape of the damage-stage curves in the case studies. The synthetic basin experiments showed that EAD is sensitive to the location of the upper and lower bounds of the damage-stage functions. In general, the case studies verified that the large basin is more sensitive to flow-exceedance probability uncertainty due to record length than to stage-flow uncertainty. The small basin is usually more sensitive to flow-exceedance probability uncertainty, except for situations of long record length and high stage-flow uncertainty. The large basin is always more sensitive to record length than the small basin, and the small basin is always more sensitive to stage-flow uncertainty than the large basin for the ranges of values examined. The case study results can be seen in Figures 44 and 45, and compared to the results of the synthetic basins in Figures 33 and 34.

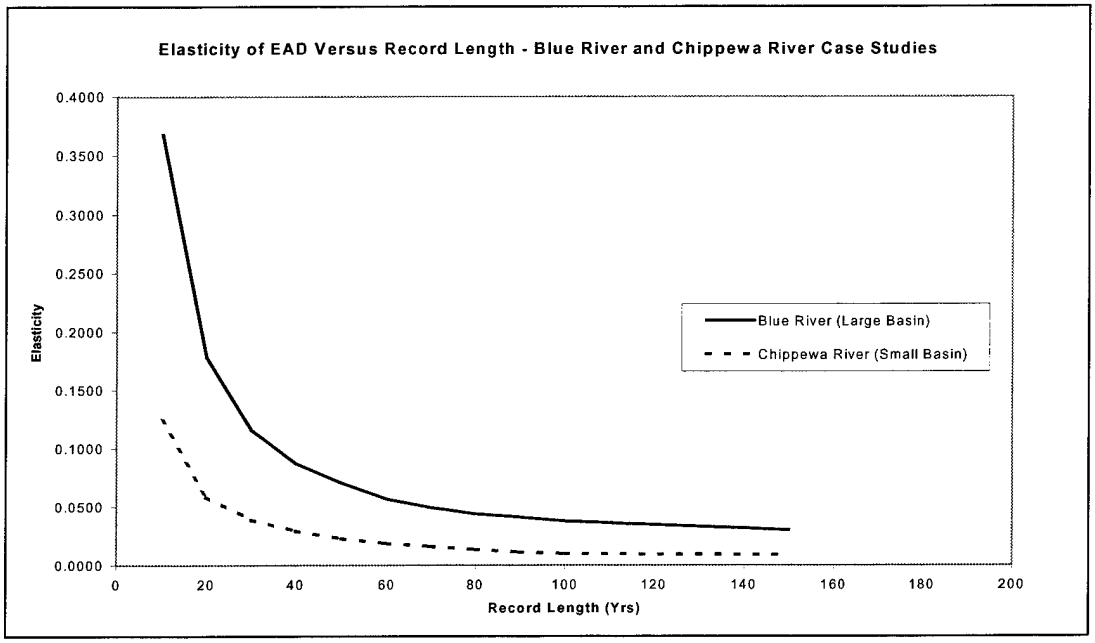

Figure 44. Elasticity of EAD Versus Record Length – Case Studies

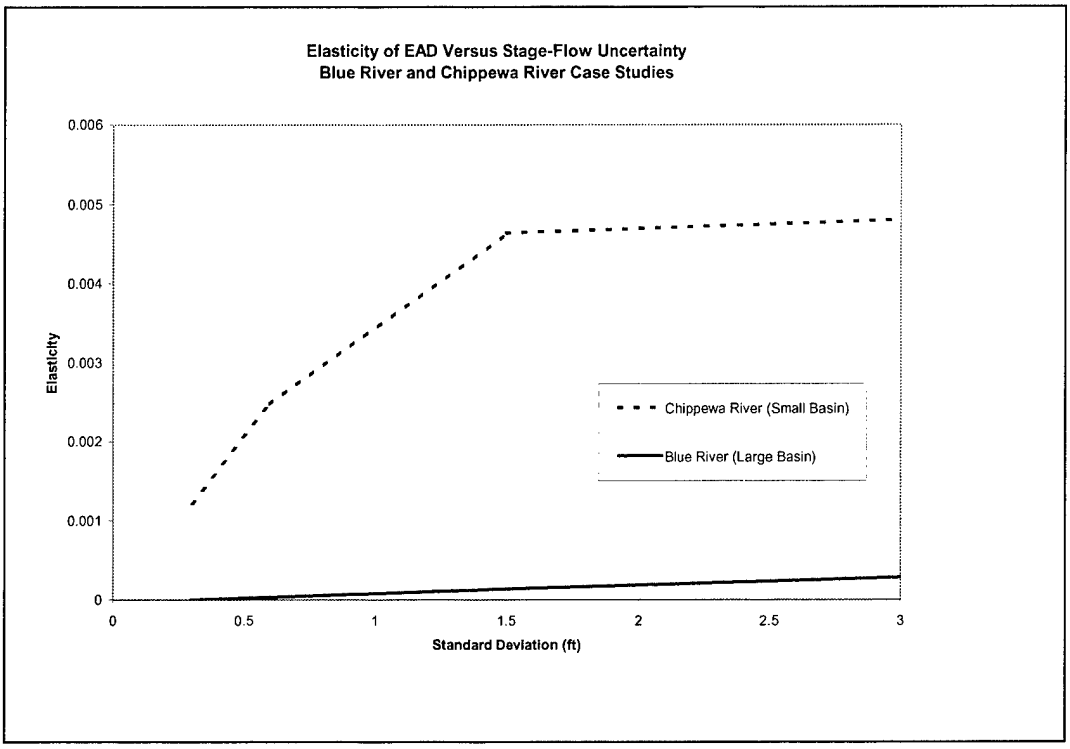

Figure 45. Elasticity of EAD Versus Stage-Flow Uncertainty – Case Studies

The sensitivity of EAD reduction to uncertainty for the case studies followed generally the same trends as for the synthetic basins, with differences due to the shape of the damage-stage function. The trends of EAD elasticity differed some from the trends of EAD, depending on the height of the levee. While both synthetic damage-stage functions were piecewise linear approximations to an S-shaped curve that started and ended at the same frequencies as one another, the case studies had different shapes and started and ended at different frequencies. The case study damage-stage curves are shown in Figures 46 and 47.

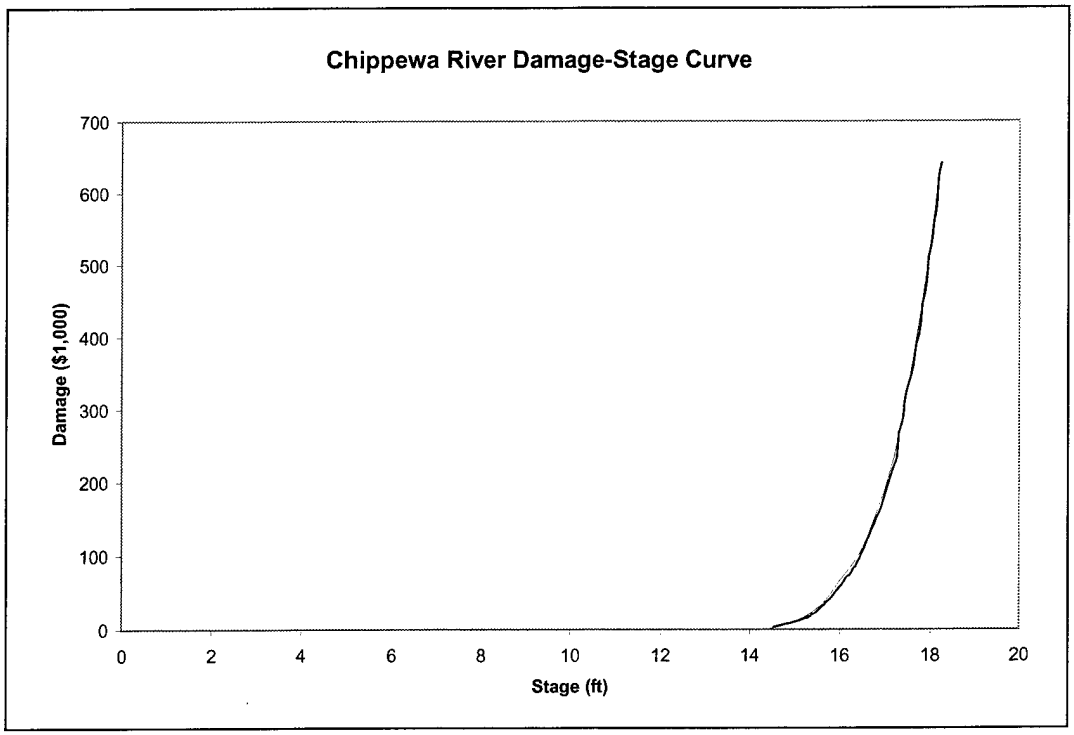

Figure 46. Chippewa River Case Study Damage-Stage Curve

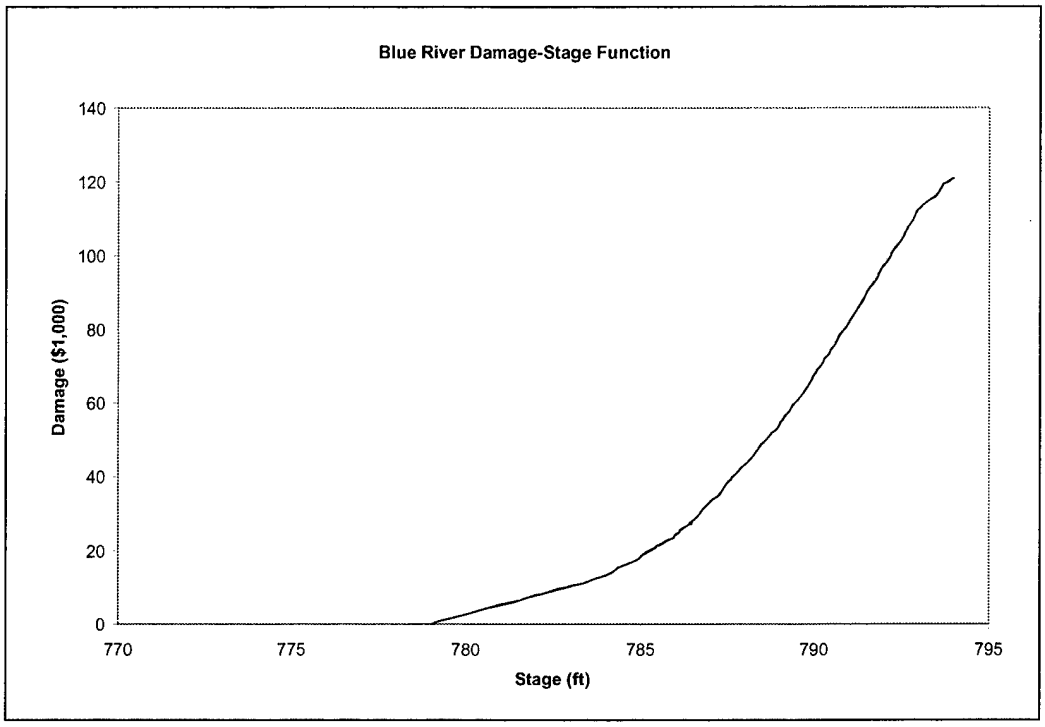

Figure 47. Blue River Case Study Damage-Stage Curve

While the synthetic damage-stage functions both begin at the mean stage associated with the 2-year (0.5 exceedance probability) event and maximize at the 500-year (0.002 exceedance probability) event, the case study functions cover different ranges. The Chippewa River damage-stage function begins at the mean stage associated with the 1.4-year (0.7 exceedance probability) event and maximizes at the mean stage associated with the 500-year event (0.002 exceedance probability). The Blue River damage-stage function begins at the mean stage associated approximately with the 1-year event (0.999 exceedance probability) and maximizes at the mean stage associated with the 500-year (0.002 exceedance probability) event. These different beginning and ending points of the damage-stage curves affect EAD, EAD reduction and their elasticity as discussed in the sensitivity analysis on the lower and upper bounds of the synthetic damage-stage functions. The combined effects of different shapes and

ranges of the damage-stage curves are the main causes of the irregularities and differences in the elasticity trends, as shown in Figures 48 through 51. Case study results in Figures 48 through 51 can be compared with the synthetic case results in Figures 36 and 37.

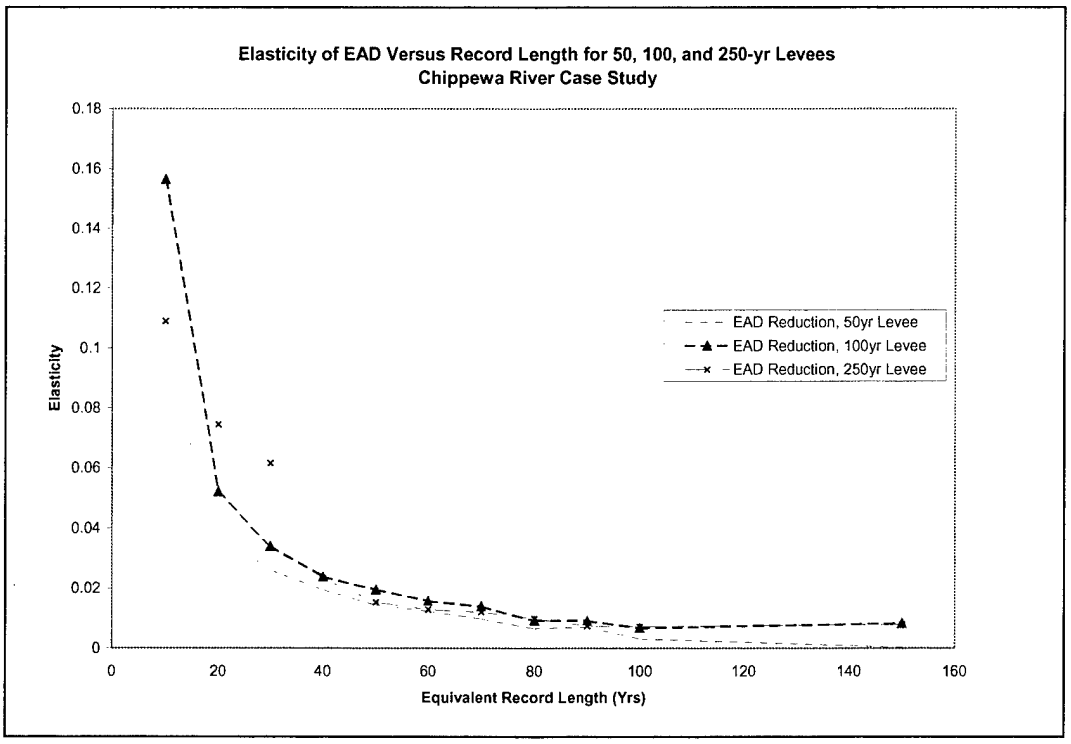

Figure 48. Elasticity of EAD Reduction Versus Record Length, Chippewa River (Small Basin)

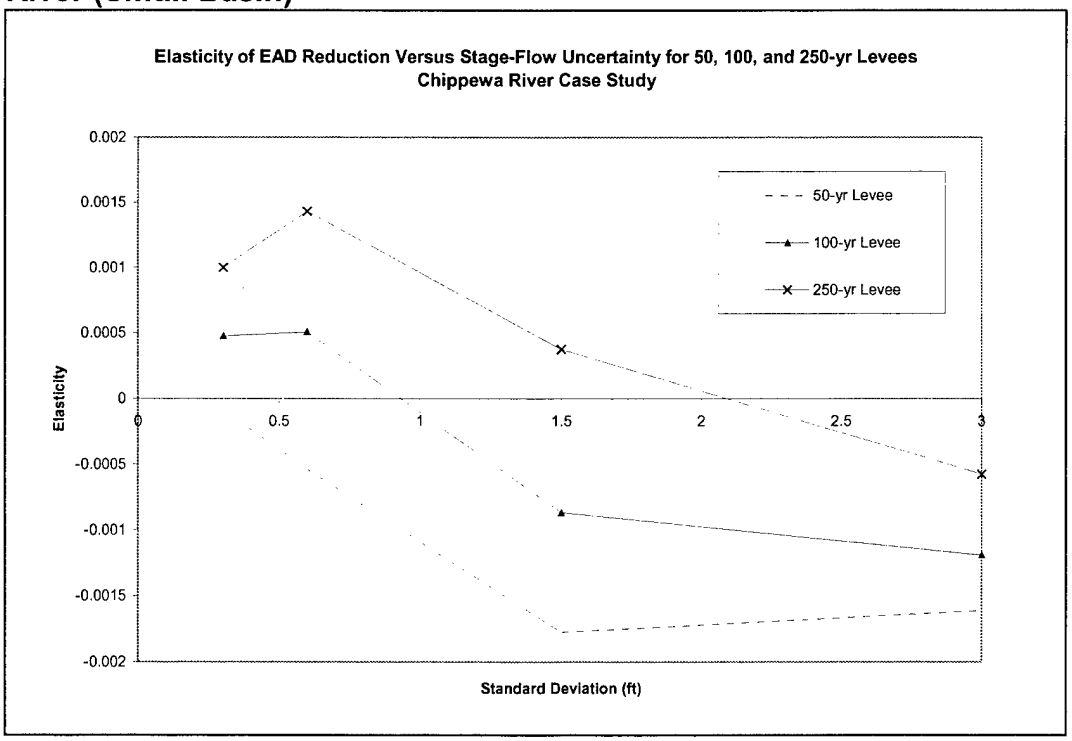

Figure 49. Elasticity of EAD Reduction Versus Stage-Flow Uncertainty, Chippewa River (Small Basin)

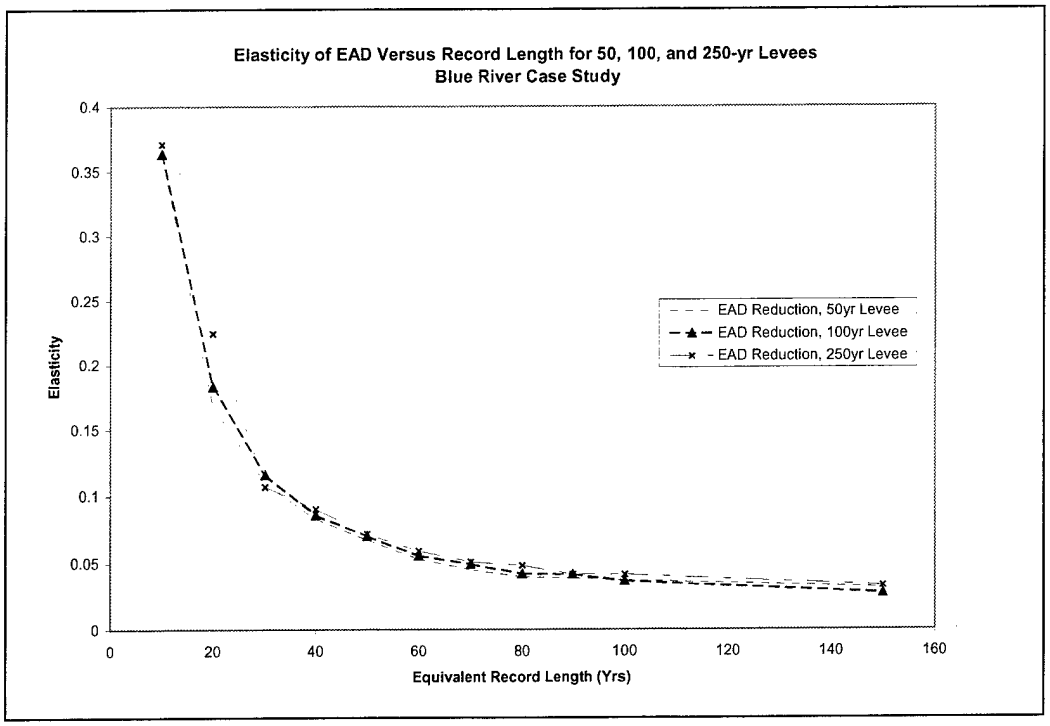

Figure 50. Elasticity of EAD Reduction Versus Record Length – Blue River (Large Basin)

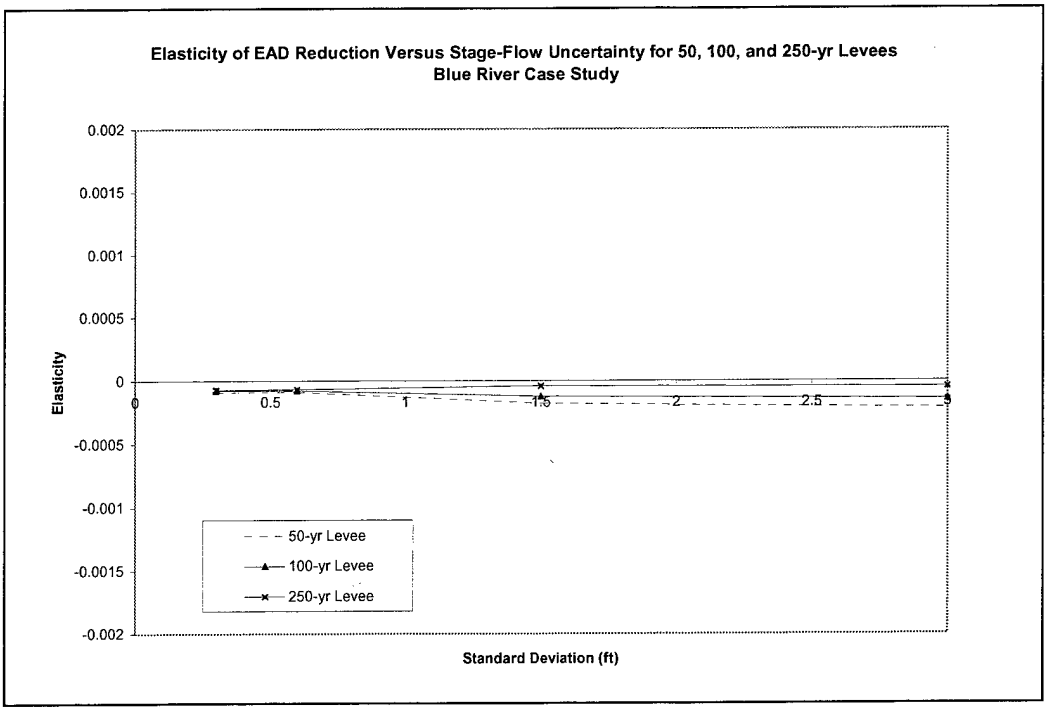

Figure 51. Elasticity of EAD Reduction Versus Stage-Flow Uncertainty – Blue River (Large Basin)

Chapter 5

Conclusions

The results of the numerical experiments showed the relative effect of each variable on EAD and EAD reduction, with some differences between the large basin and the small basin. In summary, EAD and EAD reduction were sensitive to the following variables in the order of increasing importance given in Tables 7 and 8.

Table 7. Large Basin Order of Elasticity

EAD	EAD Reduction
1. Flow-Exceedance Probability Skew	Flow-Exceedance Probability Skew
2. Damage-Stage Inflection Pt "B"	Damage-Stage Inflection Pt "B"
3. Damage-Stage Inflection Pt "A"	Damage-Stage Inflection Pt "A"
4. Flow-Exceedance Probability S. Dev.	Flow-Exceedance Probability Mean
5. Flow-Exceedance Probability Mean	Flow-Exceedance Probability S. Dev.
6. Stage-Flow Function "C" Parameter	Stage-Flow Function "C" Parameter
7. Damage-Stage Upper Bound	Damage-Stage Upper Bound
8. Damage-Stage Lower Bound	Damage-Stage Lower Bound
9. Stage-Flow Function Slope, "B"	Stage-Flow Function Slope, "B"

Table 8. Small Basin Order of Elasticity

EAD	EAD Reduction
1. Flow-Exceedance Probability Skew	Flow-Exceedance Probability Skew
2. Damage-Stage Inflection Pt "B"	Damage-Stage Inflection Pt "B"
3. Flow-Exceedance Probability Mean	Flow-Exceedance Probability Mean
4. Damage-Stage Inflection Pt "A"	Damage-Stage Inflection Pt "A"
5. Flow-Exceedance Probability S. Dev.	Flow-Exceedance Probability S. Dev.
6. Stage-Flow Function "C" Parameter	Stage-Flow Function "C" Parameter
7. Damage-Stage Upper Bound	Stage-Flow Function Slope, "B"
8. Stage-Flow Function Slope, "B"	Damage-Stage Upper Bound
9. Damage-Stage Lower Bound	Damage-Stage Lower Bound

The range of EAD elasticity calculated for the sensitivity analysis can be seen in Figure 52 and for sensitivity to uncertainty in Figure 53.

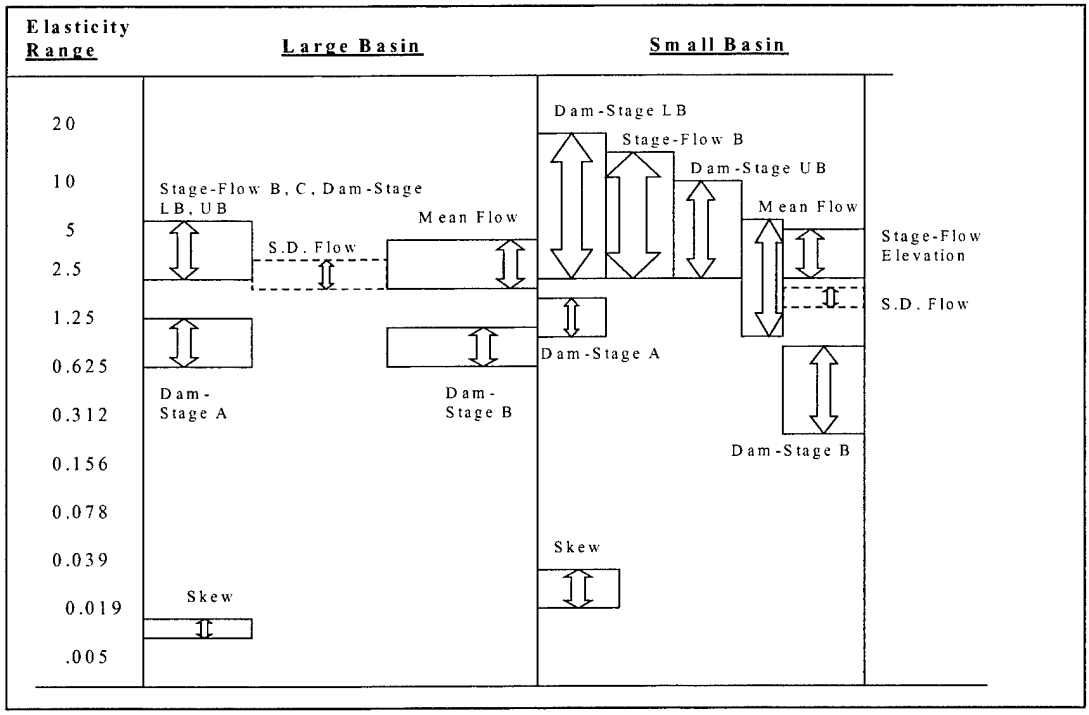

Figure 52. Sensitivity Analysis Summary

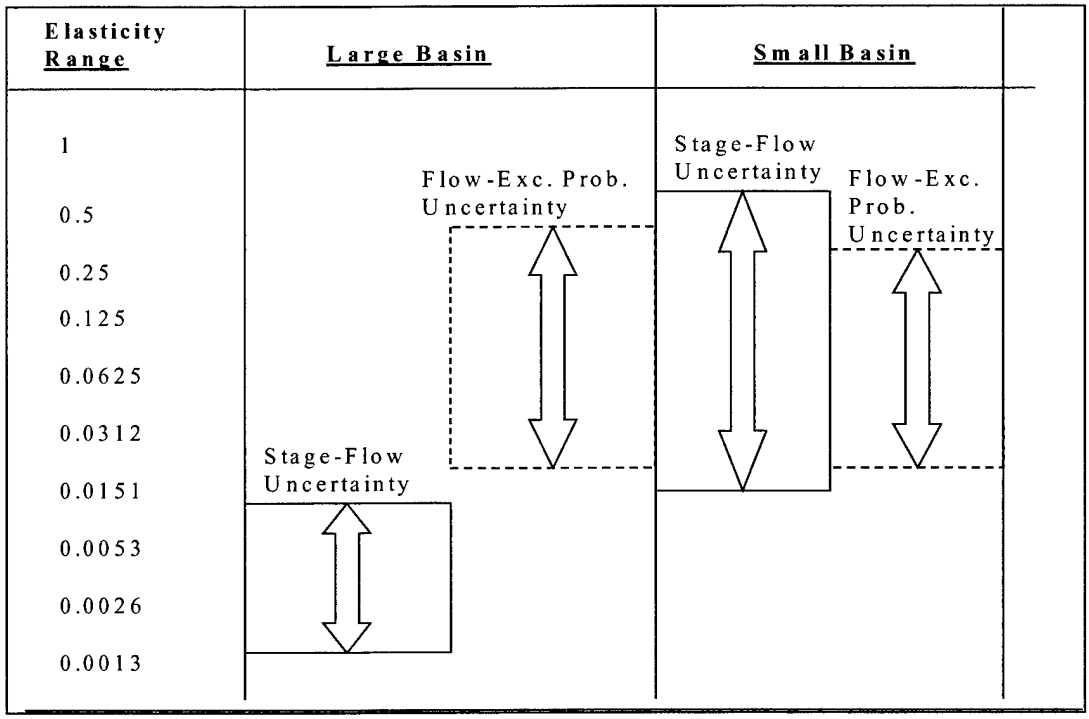

Figure 53. Sensitivity to Uncertainty Analysis Summary

As for the first set of numerical experiments, the sensitivity of EAD and EAD reduction to each type of uncertainty depended on the size of the basin and initial value of uncertainty. In general, EAD and EAD reduction are most sensitive to flow-exceedance probability uncertainty, followed by stage-flow uncertainty and damage-stage uncertainty. However, EAD and EAD reduction become more sensitive to stage-flow uncertainty for a small basin with a record length of less than about 55 years, and a standard deviation of stage-flow error of greater than about 1.5 feet (See Figures 39, 40, 42 and 43). These results are consistent with the uncertainty analysis results, which show that stage-flow uncertainty has the greatest contribution to uncertainty in EAD for the small basin, whereas the flow-exceedance probability uncertainty has the greatest contribution to uncertainty in EAD for the large basin under these conditions (See Figures 47 through 49).

In general, the case studies verified relative sensitivities to uncertainty for sample data sets. However, the case studies also showed that the relative sensitivities change for different shaped damage-stage curves. In the case studies used, EAD for the small basin (Chippewa River) was more sensitive to flow-exceedance probability uncertainty over a larger range of record lengths than EAD for the synthetic small basin. As with the synthetic basins, EAD for the large basin (Blue River) was more sensitive than the small basin (Chippewa River) to flow-exceedance probability uncertainty, and EAD for the small basin was more sensitive than EAD for the large basin to stage-flow uncertainty.

Based on the results summarized above, several trends emerged that could be useful in federal investment decision-making. Variables with the highest elasticity are those that have the most potential to improve estimates of EAD and EAD reduction. It may be worth the extra expenditure to refine the best estimate of a particular function or to reduce the uncertainty if the cost is small compared to the benefits received.

5.1 Recommendations for Investment

The results of the sensitivity analyses can be used to help make investment decisions to improve estimates of EAD and EAD reduction. For instance, if there is a small data set (i.e., less than 10-year record) and funding to improve the estimate of EAD reduction, it may be wise to wait another year or more to reduce the hydrologic uncertainty. The expected benefits of waiting a year would be affected by a combination of the reduction in hydrologic uncertainty and a slight change in the flow-exceedance probability function parameters (Davis, et. al., 1972). The benefits could be estimated as the difference between the EAD with the current data minus the EAD with one more year of data. The expected costs of waiting another year are a combination of any damage suffered during that year minus the annualized cost avoided by deferring construction for one year (Davis, et. al., 1972).

Along the same lines, it might be wiser to refine the estimate of the stage-flow curve or the damage-stage relationship by reducing the uncertainty and refining the most likely curves. The benefits of improving the estimate of EAD in this manner can be assessed using the value of additional information, as described in Chapter 2. The

sensitivity analyses demonstrate over which range of function values the investor would get the greatest improvement in EAD and EAD reduction values, and hence the most benefit. It is most important to get an accurate estimate of the variables with the highest elasticity, such as stage-flow function shape, and least important to get an accurate estimate of the variables with the lowest elasticity, such as flow-exceedance probability skew.

5.2 Regional Differences

Regional differences in EAD and EAD reduction sensitivity to primary input function parameters occur, especially if the LPIII distribution fits regional flow data poorly. Graphical flow-exceedance probability curves or curves better defined by distributions other than the LPIII may affect the elasticity of EAD and EAD reduction differently, and affect the recommendations for investment. Reservoir regulation and flow augmentations are some factors that can contribute to these differences.

Regional differences in EAD and EAD reduction sensitivity to primary input function parameters also occur due to differences in the shape of the stage-flow curve. For instance, water in a narrow channel and floodplain will tend to rise faster than in a wide channel and floodplain with the same flow capacity. Whether streamflow is generated by short, strong bursts of rainfall or gradual melting of snowpack can affect the shape of the channel and stage-flow curve significantly. Likewise, regional development patterns and land use characteristics are the main contributors to differences in stage-damage curves and the sensitivity of EAD to changes in the curve.

5.3 Further Study

In continuation of the work completed for this study, additional numerical experiments are recommended to further develop Risk-based Analysis. Similar tests could be completed on smaller and larger basins, different shaped (or differently defined) damage curves, or different flow-exceedance probability distributions. Further testing is also recommended to test the sensitivity of levee reliability measures in HEC-FDA. The study could be extended to include uncertainty with flow regulation.

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APPENDIX A. NUMERICAL RESULTS

APPENDIX A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name FFSM

Parameter Value	ΔParameter Value	EAD	EAD50	EAD100	EAD250	S	E	S50	E50	S100	E100	S250	E250
700	0	0.0857	0.0189	0.0096	0.0040								
650	50	0.0595	0.0106	0.0052	0.0020	0.00052	4.28	0.00036	3.74	0.00044	4.00	0.00048	4.14
600	100	0.0393	0.0056	0.0025	0.0000	0.00046	3.79	0.00033	3.46	0.00039	3.61	0.00042	3.63
550	150	0.0245	0.0025	0.0000	0.0000	0.00041	3.33	0.00030	3.13	0.00034	3.16	0.00038	3.27
500	200	0.0145	0.0000	0.0000	0.0000	0.00036	2.91	0.00026	2.74	0.00031	2.84	0.00034	2.88
450	250	0.0083	0.0000	0.0000	0.0000	0.00031	2.53	0.00023	2.45	0.00027	2.49	0.00029	2.52
400	300	0.0049	0.0000	0.0000	0.0000	0.00027	2.20	0.00021	2.16	0.00024	2.18	0.00026	2.19
350	350	0.0033	0.0000	0.0000	0.0000	0.00024	1.92	0.00018	1.90	0.00021	1.91	0.00022	1.92
						MinE	1.92	MinE50	1.90	MinE100	1.91	MinE250	2.88
						MaxE	4.28	MaxE50	3.74	MaxE100	4.00	MaxE250	4.14

APPENDIX A

Output File -Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name FFSS

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.08574	0.01914	0.00962	0.00402	0.14	0.00								
0.19421	0.02013	0.00988	0.00390	0.24	0.10	1.08	1.77	1.07	2.26	1.08	1.99	1.09	1.86
0.26719	0.01976	0.01002	0.00399	0.34	0.20	0.91	1.48	0.90	1.90	0.91	1.66	0.91	1.55
0.28373	0.02000	0.01002	0.00398	0.37	0.23	0.86	1.41	0.86	1.80	0.86	1.58	0.86	1.48
						MinE	1.41	MinE50	1.80	MinE100	1.58	MinE250	1.48
						MaxE	1.77	MaxE50	2.26	MaxE100	1.99	MaxE250	1.86

APPENDIX A

Output File -Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name FFSG

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.06636	0.00193	0.00000	0.00000	-0.70	0.60	-0.028	0.033	-0.003	0.005	-0.015	0.020	-0.023	0.029
0.06953	0.00380	0.00000	0.00000	-0.60	0.50	-0.027	0.033	-0.002	0.002	-0.012	0.015	-0.021	0.027
0.07269	0.00614	0.00148	0.00000	-0.50	0.40	-0.026	0.031	0.000	0.000	-0.010	0.014	-0.019	0.023
0.07561	0.00855	0.00274	0.00000	-0.40	0.30	-0.025	0.030	0.002	-0.003	-0.008	0.011	-0.015	0.019
0.07831	0.01124	0.00416	0.00002	-0.30	0.20	-0.024	0.028	0.003	-0.004	-0.006	0.008	-0.009	0.012
0.08079	0.01392	0.00605	0.00189	-0.20	0.10	-0.023	0.027	0.004	-0.005	-0.006	0.008	-0.013	0.016
0.08304	0.01652	0.00771	0.00289	-0.10	0.00								
0.08505	0.01913	0.00962	0.00401	0.00	-0.10	-0.020	0.024	0.006	-0.009	-0.001	0.001	-0.009	0.011
0.08686	0.02154	0.01163	0.00526	0.1	-0.20	-0.019	0.023	0.006	-0.009	0.001	-0.001	-0.007	0.009
0.08790	0.02395	0.01360	0.00664	0.2	-0.30	-0.016	0.020	0.009	-0.013	0.003	-0.005	-0.004	0.005
0.08928	0.02630	0.01533	0.00783	0.3	-0.40	-0.016	0.019	0.009	-0.013	0.003	-0.005	-0.003	0.004
0.09048	0.02859	0.01725	0.00919	0.4	-0.50	-0.015	0.018	0.009	-0.014	0.004	-0.006	-0.002	0.003
						MinE	0.018	MinE50	-0.014	MinE100	-0.006	MinE250	0.003
						MaxE	0.033	MaxE50	0.005	MaxE100	0.020	MaxE250	0.029

APPENDIX A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name FFLM

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.06890	0.01867	0.00966	0.00397	25,000	0								
0.06472	0.01698	0.00868	0.00357	24,500	500	0.000008	3.03	0.000005	2.48	0.000006	2.70	0.000008	2.91
0.06071	0.01527	0.00776	0.00317	24,000	1,000	0.000008	2.97	0.000005	2.38	0.000006	2.65	0.000007	2.85
0.05673	0.01388	0.00709	0.00278	23,500	1,500	0.000008	2.94	0.000005	2.45	0.000006	2.70	0.000007	2.82
0.05277	0.01256	0.00638	0.00239	23,000	2,000	0.000008	2.93	0.000005	2.49	0.000006	2.71	0.000007	2.80
0.04933	0.01123	0.00568	0.00212	22,500	2,500	0.000008	2.84	0.000005	2.41	0.000006	2.63	0.000007	2.73
0.04597	0.00990	0.00496	0.00188	22,000	3,000	0.000008	2.77	0.000005	2.35	0.000006	2.56	0.000007	2.67
0.04264	0.00886	0.00424	0.00163	21,500	3,500	0.000008	2.72	0.000005	2.34	0.000006	2.51	0.000007	2.63
0.03921	0.00774	0.00381	0.00139	21,000	4,000	0.000007	2.69	0.000005	2.33	0.000006	2.52	0.000007	2.61
0.03594	0.00692	0.00336	0.00073	20,500	4,500	0.000007	2.66	0.000005	2.35	0.000006	2.50	0.000007	2.54
0.03313	0.00615	0.00290	0.00000	20,000	5,000	0.000007	2.60	0.000005	2.31	0.000006	2.45	0.000006	2.45
0.03039	0.00538	0.00245	0.00000	19,500	5,500	0.000007	2.54	0.000005	2.28	0.000006	2.40	0.000006	2.42
0.02801	0.00458	0.00207	0.00000	19,000	6,000	0.000007	2.47	0.000004	2.22	0.000006	2.34	0.000006	2.37
0.02561	0.00388	0.00179	0.00000	18,500	6,500	0.000007	2.42	0.000004	2.18	0.000005	2.30	0.000006	2.33
0.02325	0.00340	0.00152	0.00000	18,000	7,000	0.000007	2.37	0.000004	2.16	0.000005	2.26	0.000006	2.29
0.02098	0.00291	0.00124	0.00000	17,500	7,500	0.000006	2.32	0.000004	2.13	0.000005	2.22	0.000006	2.26
0.01904	0.00241	0.00000	0.00000	17,000	8,000	0.000006	2.26	0.000004	2.09	0.000005	2.12	0.000006	2.21
0.01722	0.00197	0.00000	0.00000	16,500	8,500	0.000006	2.21	0.000004	2.05	0.000005	2.09	0.000006	2.16
0.01553	0.00167	0.00000	0.00000	16,000	9,000	0.000006	2.15	0.000004	2.01	0.000005	2.05	0.000005	2.11
0.01401	0.00138	0.00000	0.00000	15,500	9,500	0.000006	2.10	0.000004	1.97	0.000005	2.01	0.000005	2.06
0.01255	0.00102	0.00000	0.00000	15,000	10,000	0.000006	2.04	0.000004	1.93	0.000005	1.97	0.000005	2.02
0.01116	0.00000	0.00000	0.00000	14,500	10,500	0.000005	2.00	0.000004	1.85	0.000005	1.93	0.000005	1.97
0.00994	0.00000	0.00000	0.00000	14,000	11,000	0.000005	1.94	0.000004	1.82	0.000004	1.89	0.000005	1.92
0.00890	0.00000	0.00000	0.00000	13,500	11,500	0.000005	1.89	0.000004	1.79	0.000004	1.85	0.000005	1.88
0.00794	0.00000	0.00000	0.00000	13,000	12,000	0.000005	1.84	0.000004	1.75	0.000004	1.80	0.000005	1.83
0.00705	0.00000	0.00000	0.00000	12,500	12,500	0.000005	1.80	0.000003	1.72	0.000004	1.76	0.000005	1.78
						MinE	1.80	MinE50	1.72	MinE100	1.76	MinE250	1.78
						MaxE	3.03	MaxE50	2.49	MaxE100	2.71	MaxE250	2.91

APPENDIX A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name FFLS

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.06890	0.01867	0.00966	0.00397	0.22	0.00								
0.13808	0.02002	0.01003	0.00400	0.32	0.10	0.69	2.21	0.68	2.97	0.69	2.56	0.69	2.34
0.19747	0.02014	0.00998	0.00398	0.42	0.20	0.64	2.05	0.64	2.78	0.64	2.38	0.64	2.18
0.24357	0.01991	0.00997	0.00399	0.52	0.30	0.58	1.86	0.58	2.53	0.58	2.16	0.58	1.97
0.26275	0.01988	0.00993	0.00401	0.57	0.35	0.55	1.77	0.55	2.41	0.55	2.05	0.55	1.88
						MinE	1.77	MinE50	2.41	MinE100	2.05	MinE250	1.88
						MaxE	2.21	MaxE50	2.97	MaxE100	2.56	MaxE250	2.34

APPENDIX A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name FFLG

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.32974	0.18510	0.11890	0.06103	-0.70	0.60	0.030	0.0095	0.030	0.0236	0.053	0.0297	0.070	0.0311
0.32679	0.18575	0.12205	0.06636	-0.60	0.50	0.030	0.0095	0.029	0.0226	0.052	0.0289	0.068	0.0300
0.32423	0.18616	0.12501	0.07105	-0.50	0.40	0.031	0.0099	0.028	0.0224	0.051	0.0284	0.067	0.0294
0.32142	0.18623	0.12759	0.07506	-0.40	0.30	0.032	0.0102	0.028	0.0223	0.050	0.0278	0.066	0.0292
0.31810	0.18605	0.12974	0.07876	-0.30	0.20	0.031	0.0099	0.027	0.0211	0.047	0.0264	0.064	0.0283
0.31516	0.18572	0.13153	0.08241	-0.20	0.10	0.033	0.0105	0.027	0.0216	0.047	0.0264	0.062	0.0275
0.31190	0.18520	0.13299	0.08539	-0.10	0.00								
0.30886	0.18457	0.13418	0.08795	0.00	-0.10	0.030	0.0097	0.024	0.0190	0.042	0.0236	0.056	0.0247
0.30563	0.18381	0.13511	0.09014	0.10	-0.20	0.031	0.0101	0.024	0.0193	0.042	0.0234	0.055	0.0243
0.30251	0.18294	0.13582	0.09200	0.20	-0.30	0.031	0.0100	0.024	0.0188	0.041	0.0228	0.053	0.0235
0.29940	0.18195	0.13632	0.09358	0.30	-0.40	0.031	0.0100	0.023	0.0183	0.040	0.0221	0.052	0.0228
0.29608	0.18078	0.13659	0.09487	0.40	-0.50	0.032	0.0101	0.023	0.0180	0.039	0.0217	0.051	0.0223
						MinE	0.0095	MinE50	0.0180	MinE100	0.0217	MinE250	0.0223
						MaxE	0.0105	MaxE50	0.0236	MaxE100	0.0297	MaxE250	0.0311

~~Appendix A~~

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name SFSB

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.08431	0.03429	0.02087	0.01023	0.004	0.000								
0.00260	0.00000	0.00000	0.00000	0.002	-0.002	40.86	1.94	23.71	1.90	30.42	1.92	35.74	1.93
0.00651	0.00000	0.00000	0.00000	0.003	-0.001	77.80	3.69	43.51	3.48	56.93	3.59	67.57	3.65
0.28832	0.19555	0.14766	0.09909	0.005	0.001	204.01	9.68	42.75	3.42	77.22	4.87	115.15	6.22
0.52648	0.42875	0.36286	0.28258	0.006	0.002	221.09	10.49	23.86	1.91	50.09	3.16	84.91	4.58
						MinE	1.94	MinE50	1.90	MinE100	1.92	MinE250	1.93
						MaxE	10.49	MaxE50	3.48	MaxE100	4.87	MaxE250	6.22

~~Appendix A~~

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name SFSC

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.08431	0.03429	0.02087	0.01023	1.55	0.00								
0.00515	0.00000	0.00000	0.00000	0	1.55	-0.0511	0.939	-0.03	0.897	-0.04	0.919	-0.04	0.930
0.03129	0.00975	0.00566	0.00242	1	0.55	-0.0964	1.772	-0.05	1.605	-0.07	1.680	-0.08	1.720
0.16985	0.08372	0.05390	0.02881	2	-0.45	-0.1901	3.495	-0.08	2.487	-0.12	2.851	-0.15	3.113
0.55884	0.41495	0.31009	0.19320	3	-1.45	-0.3273	6.017	-0.06	2.006	-0.13	3.122	-0.20	4.207
0.92237	0.89436	0.82279	0.67967	4	-2.45	-0.3421	6.289	0.009	-0.278	-0.015	0.360	-0.069	1.440
0.99281	0.99167	0.99020	0.98762	5	-3.45	-0.2633	4.841	0.014	-0.439	0.018	-0.431	0.020	-0.418
						MinE	0.94	MinE50	-0.44	MinE100	-0.43	MinE250	-0.418
						MaxE	6.29	MaxE50	2.49	MaxE100	3.12	MaxE250	4.21

Appendix A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name SFLB

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.06888	0.01865	0.00968	0.00396	0.0002	0.0000								
0.00330	0.00000	0.00000	0.00000	0.0001	-0.0001	655.80	1.90	469.30	1.87	559.00	1.89	616.20	1.90
0.26147	0.14569	0.10326	0.06433	0.0003	0.0001	1925.90	5.59	655.50	2.61	990.10	3.34	1322.2	4.07
0.47401	0.33387	0.26465	0.19253	0.0004	0.0002	2025.65	5.88	449.55	1.79	750.80	2.54	1082.8	3.34
0.64298	0.51634	0.43734	0.34552	0.0005	0.0003	1913.67	5.56	254.70	1.01	488.13	1.65	775.13	2.39
						MinE	1.90	MinE50	1.01	MinE100	1.65	MinE250	1.90
						MaxE	5.88	MaxE50	2.61	MaxE100	3.34	MaxE250	4.07

Appendix A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name SFLC

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.06888	0.01865	0.00968	0.00396	7.89	0.00								
0.01932	0.00391	0.00191	0.00000	5	-2.89	0.0171	1.96	0.01	1.89	0.01	1.93	0.02	1.92
0.02998	0.00694	0.00352	0.00123	6	-1.89	0.0206	2.36	0.01	2.26	0.02	2.31	0.02	2.33
0.04706	0.01196	0.00620	0.00233	7	-0.89	0.0245	2.81	0.02	2.67	0.02	2.75	0.02	2.76
0.07254	0.01963	0.01026	0.00417	8	0.11	0.0333	3.81	0.02	3.83	0.03	3.73	0.03	3.81
0.11046	0.03248	0.01740	0.00733	9	1.11	0.0375	4.29	0.03	3.93	0.03	4.07	0.03	4.18
0.16584	0.05325	0.02861	0.01243	10	2.11	0.0460	5.26	0.03	4.64	0.04	4.93	0.04	5.10
						MinE	1.96	MinE50	1.89	MinE100	1.93	MinE250	1.92
						MaxE	5.26	MaxE50	4.64	MaxE100	4.93	MaxE250	5.10

~~Appendix A~~

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name DSSU

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.06672	0.01903	0.00966	0.00401	6.20	2.00	0.023	9.15	0.017	9.93	0.021	10.53	0.022	10.05
0.03382	0.01300	0.00792	0.00367	7.20	1.00	0.013	5.24	0.007	4.05	0.010	5.08	0.012	5.41
0.02064	0.00670	0.00465	0.00247	8.20	0.00								
0.01502	0.00326	0.00234	0.00141	9.20	-1.00	0.006	2.23	0.002	1.28	0.003	1.70	0.005	2.06
0.01242	0.00202	0.00125	0.00072	10.20	-2.00	0.004	1.63	0.002	1.04	0.002	1.24	0.003	1.46
						MinE	1.63	MinE50	1.04	MinE100	1.24	MinE250	1.46
						MaxE	9.15	MaxE50	9.93	MaxE100	10.53	MaxE250	10.05

Appendix A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name DSSL

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.15128	0.01549	0.00839	0.00364	2.20	2.000	0.065	13.29	0.061	18.36	0.063	16.67	0.065	14.96
0.06817	0.01214	0.00707	0.00334	3.20	1.000	0.048	9.67	0.042	12.68	0.045	11.85	0.047	10.79
0.02064	0.00670	0.00465	0.00247	4.20	0.000								
0.01182	0.00428	0.00331	0.00199	4.60	-0.400	0.022	4.49	0.016	4.82	0.019	4.91	0.021	4.82
0.00545	0.00205	0.00152	0.00104	5.20	-1.000	0.015	3.09	0.011	3.18	0.012	3.17	0.014	3.18
0.00266	0.00019	0.00016	0.00013	6.20	-2.000	0.009	1.83	0.006	1.73	0.007	1.77	0.008	1.81
						MinE	1.83	MinE50	1.73	MinE100	1.77	MinE250	1.81
						MaxE	13.29	MaxE50	18.36	MaxE100	16.67	MaxE250	14.96

Appendix A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name DSSA

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.02064	0.00670	0.00465	0.00247	0.3333	0.0000								
0.03597	0.00833	0.00479	0.00224	0.1667	0.1667	0.092	1.49	0.082	1.97	0.091	1.90	0.093	1.71
0.01259	0.00219	0.00142	0.00088	0.5000	-0.1667	0.048	0.78	0.021	0.51	0.029	0.60	0.039	0.71

Appendix A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name DSSB

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.02064	0.00670	0.00465	0.00247	0.667	0.000								
0.02446	0.01046	0.00737	0.00362	0.500	0.167	0.023	0.74	0.000	0.02	0.007	0.28	0.016	0.59
0.01906	0.00515	0.00344	0.00179	0.833	-0.167	0.009	0.31	0.000	0.01	0.002	0.09	0.005	0.20

~~Appendix A~~

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name DSLU

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.13191	0.02003	0.01001	0.00399	19.60	4.00	0.016	5.49	0.016	7.39	0.016	6.36	0.016	5.83
0.11106	0.01986	0.01001	0.00399	20.60	3.00	0.014	4.92	0.014	6.58	0.014	5.69	0.014	5.22
0.09356	0.01953	0.00997	0.00399	21.60	2.00	0.013	4.36	0.012	5.79	0.012	5.02	0.013	4.62
0.07989	0.01915	0.00984	0.00399	22.60	1.00	0.012	4.00	0.011	5.27	0.011	4.59	0.012	4.24
0.06832	0.01866	0.00968	0.00397	23.60	0.00								
0.05931	0.01764	0.00950	0.00391	24.60	-1.00	0.009	3.11	0.008	3.80	0.009	3.55	0.009	3.28
0.05151	0.01637	0.00926	0.00383	25.60	-2.00	0.008	2.90	0.007	3.45	0.008	3.30	0.008	3.06
0.04552	0.01487	0.00877	0.00375	26.60	-3.00	0.008	2.63	0.006	3.01	0.007	2.94	0.008	2.76
0.04029	0.01344	0.00822	0.00368	27.60	-4.00	0.007	2.42	0.006	2.71	0.007	2.67	0.007	2.54
						MinE	2.42	MinE50	2.71	MinE100	2.67	MinE250	2.54
						MaxE	5.49	MaxE50	7.39	MaxE100	6.36	MaxE250	5.83

~~Appendix A~~

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection
SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name DSLL

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.18474	0.01911	0.00977	0.00397	8.600	4.000	0.029	5.37	0.029	7.36	0.029	6.25	0.029	5.70
0.14952	0.01905	0.00975	0.00397	9.600	3.000	0.027	4.99	0.027	6.83	0.027	5.81	0.027	5.30
0.11804	0.01897	0.00973	0.00397	10.600	2.000	0.025	4.58	0.025	6.27	0.025	5.34	0.025	4.87
0.09060	0.01888	0.00971	0.00397	11.600	1.000	0.022	4.11	0.022	5.60	0.022	4.78	0.022	4.36
0.06832	0.01866	0.00968	0.00397	12.600	0.000								
0.05109	0.01819	0.00964	0.00396	13.600	-1.000	0.017	3.18	0.017	4.25	0.017	3.69	0.017	3.37
0.03880	0.01746	0.00960	0.00396	14.600	-2.000	0.015	2.72	0.014	3.59	0.015	3.16	0.015	2.89
0.02927	0.01645	0.00955	0.00396	15.600	-3.000	0.013	2.40	0.012	3.12	0.013	2.79	0.013	2.55
0.02240	0.01487	0.00940	0.00395	16.600	-4.000	0.011	2.12	0.011	2.67	0.011	2.45	0.011	2.25
						MinE	2.12	MinE50	2.67	MinE100	2.45	MinE250	2.25
						MaxE	5.37	MaxE50	7.36	MaxE100	6.25	MaxE250	5.70

Appendix A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean
FFSS Flow-freq, small basin, std dev
FFLG Flow-freq, large basin, skew
DSLL Damage-stage, large, lower bound
DSLA Damage-stage, large, 1st inflection

SFSB Stage-flow, small, slope
SFLC Stage-flow, large, elev of function
DSSU Damage-stage, small, upper bound
DSSB Damage-stage, small, 2nd inflection pt

Run Name DSLA

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.06832	0.01866	0.00968	0.00397	0.3333	0.0000								
0.10777	0.01870	0.00968	0.00397	0.1667	0.1667	0.237	1.15	0.236	1.59	0.237	1.35	0.237	1.23
0.04592	0.01852	0.00968	0.00397	0.5000	-0.1667	0.134	0.66	0.134	0.90	0.134	0.76	0.134	0.70

Appendix A

Output File - Sensitivity Analysis

Typical Run Names

FFLM = Flow-freq, Large basin, Mean		SFSB	Stage-flow, small, slope
FFSS	Flow-freq, small basin, std dev	SFLC	Stage-flow, large, elev of function
FFLG	Flow-freq, large basin, skew	DSSU	Damage-stage, small, upper bound
DSLL	Damage-stage, large, lower bound	DSSB	Damage-stage, small, 2nd inflection pt
DSLA	Damage-stage, large, 1st inflection	DSLB	Damage-stage, large, 2nd inflection

Run Name DSLB

EAD	EAD50	EAD100	EAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
0.06832	0.01919	0.00979	0.00397	0.667	0.000								
0.08504	0.01866	0.00968	0.00397	0.500	0.167	0.100	0.98	0.104	1.40	0.101	1.15	0.100	1.04
0.05784	0.01595	0.00917	0.00394	0.833	-0.167	0.063	0.61	0.043	0.59	0.059	0.67	0.063	0.65

APPENDIX A

Output File - Sensitivity to Uncertainty
Flow Frequency Function

Typical Run Names

FFLN Flow-freq, large, record length
SFLS Stage-flow, large, std dev
DSSS Damage-stage, small, std dev

Run Name FFSN

EAD	ΔEAD50	ΔEAD100	ΔEAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
9.77	6.02	7.30	8.30	10	190	0.0109	0.2830	0.00147	0.0513	0.0033	0.0994	0.0055	0.1508
8.66	5.89	7.01	7.80	20	180	0.0053	0.1385	0.00083	0.0290	0.0019	0.0566	0.0030	0.0826
8.31	5.85	6.90	7.62	30	170	0.0036	0.0932	0.00065	0.0225	0.0014	0.0406	0.0021	0.0583
8.13	5.82	6.83	7.52	40	160	0.0027	0.0698	0.0005	0.0174	0.0010	0.0300	0.0016	0.0448
8.01	5.79	6.79	7.45	50	150	0.0021	0.0537	0.00033	0.0116	0.0008	0.0240	0.0013	0.0349
7.94	5.78	6.76	7.41	60	140	0.0017	0.0445	0.00029	0.0100	0.0006	0.0193	0.0011	0.0295
7.90	5.78	6.75	7.39	70	130	0.0015	0.0400	0.00031	0.0107	0.0006	0.0185	0.0010	0.0275
7.85	5.76	6.73	7.35	80	120	0.0013	0.0325	0.00017	0.0058	0.0005	0.0150	0.0007	0.0207
7.82	5.76	6.72	7.34	90	110	0.0011	0.0283	0.00018	0.0063	0.0005	0.0136	0.0007	0.0200
7.79	5.75	6.70	7.31	100	100	0.0009	0.0234	1E-04	0.0035	0.0003	0.0090	0.0005	0.0138
7.74	5.75	6.69	7.29	150	50	0.0008	0.0208	0.0002	0.0070	0.0004	0.0120	0.0006	0.0165
7.70	5.74	6.67	7.26	200	0								
						MinE	0.0208	MinE50	0.0035	MinE100	0.0090	MinE250	0.0138
						MaxE	0.2830	MaxE50	0.0513	MaxE100	0.0994	MaxE250	0.1508

APPENDIX A

Output File - Sensitivity to Uncertainty
Flow Frequency Function

Typical Run Names

FFLN	Flow-freq, large, record length
SFLS	Stage-flow, large, std dev
DSSS	Damage-stage, small, std dev

Run Name FFLN

EAD	ΔEAD50	ΔEAD100	ΔEAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
8.62	4.90	6.15	7.15	10	190	0.0107	0.3243	0.00132	0.0566	0.0031	0.1117	5.3E-03	2.E-01
7.53	4.79	5.88	6.67	20	180	0.0052	0.1585	0.00078	0.0335	0.0018	0.0639	2.9E-03	9.E-02
7.18	4.74	5.77	6.49	30	170	0.0035	0.1053	0.00053	0.0228	0.0012	0.0444	2.0E-03	7.E-02
7.01	4.72	5.72	6.40	40	160	0.0026	0.0797	0.00044	0.0188	0.0010	0.0360	1.6E-03	5.E-02
6.90	4.70	5.68	6.34	50	150	0.0021	0.0627	0.00033	0.0143	0.0008	0.0288	1.3E-03	4.E-02
6.83	4.69	5.65	6.30	60	140	0.0017	0.0520	0.00029	0.0123	0.0006	0.0231	1.1E-03	3.E-02
6.78	4.68	5.63	6.27	70	130	0.0015	0.0444	0.00023	0.0099	0.0005	0.0194	9.2E-04	3.E-02
6.74	4.68	5.62	6.24	80	120	0.0013	0.0379	0.00025	0.0108	0.0005	0.0180	7.5E-04	2.E-02
6.70	4.66	5.6	6.22	90	110	0.0010	0.0303	9.1E-05	0.0039	0.0004	0.0131	6.4E-04	2.E-02
6.68	4.66	5.59	6.20	100	100	0.0009	0.0273	1E-04	0.0043	0.0003	0.0108	5.0E-04	2.E-02
6.62	4.65	5.57	6.17	150	50	0.0006	0.0182	0.0000	0.0000	0.0002	0.0072	4.0E-04	1.E-02
6.59	4.65	5.56	6.15	200	0								
						MinE	0.0182	MinE50	0.0000	MinE100	0.0072	MinE250	0.013
						MaxE	0.3243	MaxE50	0.0566	MaxE100	0.1117	MaxE250	0.171

APPENDIX A

Output File - Sensitivity to Uncertainty
Stage Flow Function

Typical Run Names

FFLN Flow-freq, large, record length
SFLS Stage-flow, large, std dev
DSSS Damage-stage, small, std dev

Run Name SFLS

EAD	ΔEAD50	ΔEAD100	ΔEAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
6.58	4.64	5.55	6.14	0	0								
6.59	4.65	5.56	6.15	0.1	0.0								
6.61	4.66	5.57	6.17	0.3	0.2	0.10	0.0015	0.05	0.0011	0.05	0.0009	0.10	0.002
6.69	4.70	5.62	6.23	0.6	0.5	0.20	0.0030	0.10	0.0022	0.12	0.0022	0.16	0.003
7.25	4.93	5.96	6.67	1.5	1.4	0.47	0.0072	0.20	0.0043	0.28	0.0051	0.37	0.006
9.06	5.60	6.98	8.02	3.0	2.9	0.85	0.0129	0.33	0.0070	0.49	0.0088	0.64	0.010
						MinE	0.0015	MinE50	0.0011	MinE100	0.0009	MinE250	0.002
						MaxE	0.0129	MaxE50	0.0070	MaxE100	0.0088	MaxE250	0.010

APPENDIX A

Output File - Sensitivity to Uncertainty
Stage Flow Function

Typical Run Names

FFLN Flow-freq, large, record length
SFLS Stage-flow, large, std dev
DSSS Damage-stage, small, std dev

Run Name SFSS

EAD	ΔEAD50	ΔEAD100	ΔEAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
7.69	5.71	6.66	7.25	0	0								
7.73	5.75	6.69	7.29	0.1	0								
7.97	5.83	6.82	7.47	0.3	0.2	1.20	0.016	0.40	0.0070	0.65	0.010	0.9000	0.0123
8.77	6.11	7.27	8.07	0.6	0.5	2.08	0.027	0.72	0.013	1.16	0.017	1.5600	0.0214
13.03	7.07	9.04	10.66	1.5	1.4	3.79	0.049	0.94	0.016	1.68	0.025	2.407143	0.0330
21.49	7.39	10.31	13.26	3.0	2.9	4.74	0.061	0.57	0.0098	1.25	0.019	2.058621	0.0282
						MinE	0.016	MinE50	0.0070	MinE100	0.010	MinE250	0.0123
						MaxE	0.061	MaxE50	0.0164	MaxE100	0.025	MaxE250	0.0330

APPENDIX A

Output File - Sensitivity to Uncertainty
Damage Stage Function

Typical Run Names

FFLN Flow-freq, large, record length
SFLS Stage-flow, large, std dev
DSSS Damage-stage, small, std dev

Run Name DSSS

EAD	ΔEAD50	ΔEAD100	ΔEAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
7.69	5.71	6.66	7.25	1	0	0	0	0	0	0	0	0	0
7.69	5.71	6.66	7.25	5	4.0	0.00	0	0	0	0	0	0	0
7.69	5.71	6.66	7.25	10	9.0	0.00	0	0	0	0	0	0	0
7.69	5.71	6.66	7.25	20	15.0	0.00	0	0	0	0	0	0	0

Mean EAD/EAD Reduction not sensitive to damage-stage uncertainty

APPENDIX A

Output File - Sensitivity to Uncertainty
Damage Stage Function

Typical Run Names

FFLN	Flow-freq, large, record length
SFLS	Stage-flow, large, std dev
DSSS	Damage-stage, small, std dev

Run Name DSLS

EAD	ΔEAD50	ΔEAD100	ΔEAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
6.58	4.64	5.55	6.14	1	0	0	0	0	0	0	0	0	0
6.58	4.64	5.55	6.14	5	4.0	0.00	0	0	0	0	0	0	0
6.58	4.64	5.55	6.14	10	9.0	0.00	0	0	0	0	0	0	0
6.58	4.64	5.55	6.14	20	15.0	0.00	0	0	0	0	0	0	0

Mean EAD/EAD Reduction not sensitive to damage-stage uncertainty

APPENDIX A

Output File - Sensitivity to Uncertainty
Stage Flow Function

Typical Run Names

FFLN Flow-freq, large, record length
SFLS Stage-flow, large, std dev
DSSS Damage-stage, small, std dev
SFSwope Stage-flow, Swope/Blue R Case Study, std dev

Run Name SFSwope

EAD	ΔEAD50	ΔEAD100	ΔEAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
				0	0								
5.29	3.77	4.37	4.85	0.01	0.0								
5.29	3.76	4.36	4.84	0.3	0.3	0.00	0	-0.03	-9E-05	-0.03448	-8E-05	-0.0345	-7E-05
5.3	3.75	4.35	4.83	0.6	0.6	0.02	3E-05	-0.03	-9E-05	-0.0339	-8E-05	-0.0339	-7E-05
5.4	3.67	4.29	4.82	1.5	1.5	0.07	0.0001	-0.07	-0.0002	-0.04698	-1E-04	-0.020	-4E-05
5.74	3.53	4.18	4.78	3.0	3.0	0.15	0.0003	-0.08	-0.0002	-0.0602	-1E-04	-0.02341	-5E-05
						MinE	0	MinE50	-0.0002	MinE100	-1E-04	MinE250	-7E-05
						MaxE	0.0003	MaxE50	-0.0001	MaxE100	-8E-05	MaxE250	-4E-05

APPENDIX A

Output File - Sensitivity to Uncertainty
Stage Flow Function

Typical Run Names

FFLN Flow-freq, large, record length
SFLS Stage-flow, large, std dev
DSSS Damage-stage, small, std dev
SFHarmon Stage-flow, Harmon/Chippewa R Case Study, std dev

Run Name SFHarmon

EAD	ΔEAD50	ΔEAD100	ΔEAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
				0	0								
68887.72	60431.19	63797.79	66403.53	0.01	0.0								
71336.29	60291.10	64675.41	68327.13	0.3	0.3	8443	0.00123	-483.07	-8E-05	3026.28	0.0005	6633.10	0.0010
78962.41	58509.03	65711.05	72011.35	0.6	0.6	17076	0.00248	-3258	-0.0005	3242.81	0.0005	9504.78	0.0014
116499.4	44455.56	55537.56	70116.19	1.5	1.5	31954	0.00464	-10722	-0.0018	-6132.79	-0.0009	2491.72	0.0004
167904.2	31309.58	41051.39	54974.27	3.0	3.0	33116	0.00481	-9740	-0.0016	-7901.01	-0.0012	-3822.49	-6E-04
						MinE	0.0012	MinE50	-0.0018	MinE100	-0.0012	MinE250	-6E-04
						MaxE	0.00481	MaxE50	-0.0001	MaxE100	0.0005	MaxE250	0.0014

APPENDIX A

Output File - Sensitivity to Uncertainty
Flow Frequency Function

Typical Run Names

FFLN Flow-freq, large, record length
SFLS Stage-flow, large, std dev
DSSS Damage-stage, small, std dev
FFHarmon Flow-freq, Harmon/Chippewa R Case Study, record length

Run Name FFHarmon

EAD	ΔEAD50	ΔEAD100	ΔEAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
77047.45	65767.68	73285.57	73285.57	10	190	42.95	0.125	28.087	0.093	49.94	0.157	36.22	0.109
72545.66	62550.12	66792.45	70856.35	20	180	20.32	0.059	11.772	0.0390	16.64	0.052	24.74	0.075
71178.29	61773.47	65646.94	69879.25	30	170	13.47	0.039	7.896	0.0261	10.88	0.034	20.45	0.062
70514.70	61378.37	65022.15	67647.95	40	160	10.17	0.030	5.920	0.0196	7.65	0.024	7.78	0.023
70063.05	61086.11	64738.37	67166.27	50	150	7.84	0.023	4.366	0.0144	6.27	0.020	5.08	0.015
69795.11	60955.20	64506.61	67001.74	60	140	6.48	0.019	3.743	0.0124	5.06	0.016	4.27	0.013
69606.10	60816.03	64379.95	66924.46	70	130	5.53	0.016	2.960	0.0098	4.48	0.014	4.01	0.012
69446.98	60671.59	64153.34	66795.06	80	120	4.66	0.014	2.003	0.0066	2.96	0.009	3.26	0.010
69317.12	60666.54	64122.92	66674.10	90	110	3.90	0.011	2.140	0.0071	2.96	0.009	2.46	0.007
69233.44	60526.88	64016.25	66642.89	100	100	3.46	0.010	0.957	0.0032	2.18	0.007	2.39	0.007
69038.88	60436.31	63930.26	66535.06	150	50	3.02	0.009	0.102	0.0003	2.65	0.008	2.63	0.008
68887.72	60431.19	63797.79	66403.53	200	0								
						MinE	0.009	MinE50	0.0003	MinE100	0.007	MinE250	0.007
						MaxE	0.125	MaxE50	0.0930	MaxE100	0.157	MaxE250	0.109

APPENDIX A

Output File - Sensitivity to Uncertainty
Flow Frequency Function

Typical Run Names

FFLN Flow-freq, large, record length
SFLS Stage-flow, large, std dev
DSSS Damage-stage, small, std dev
FFSwope Flow-freq, Swope/Blue R Case Study, record length

Run Name FFSwope

EAD	ΔEAD50	ΔEAD100	ΔEAD250	Parameter Value	ΔParameter Value	S	E	S50	E50	S100	E100	S250	E250
7.14	5.07	5.88	6.56	10	190	0.0097	0.368	0.00684	0.363	0.0079	0.364	0.00900	0.371
6.14	4.34	5.09	5.83	20	180	0.0047	0.179	0.00317	0.168	0.0040	0.183	0.00544	0.225
5.81	4.12	4.80	5.29	30	170	0.0031	0.116	0.00206	0.109	0.0025	0.116	0.00259	0.107
5.66	4.02	4.67	5.20	40	160	0.0023	0.087	0.00156	0.083	0.0019	0.086	0.00219	0.090
5.57	3.96	4.60	5.11	50	150	0.0019	0.071	0.00127	0.067	0.0015	0.070	0.00173	0.071
5.50	3.91	4.54	5.05	60	140	0.0015	0.057	0.001	0.053	0.0012	0.056	0.00143	0.059
5.46	3.88	4.51	5.01	70	130	0.0013	0.049	0.00085	0.045	0.0011	0.049	0.00123	0.051
5.43	3.86	4.48	4.99	80	120	0.0012	0.044	0.00075	0.040	0.0009	0.042	0.00117	0.048
5.41	3.85	4.47	4.96	90	110	0.0011	0.041	0.00073	0.039	0.0009	0.042	0.00100	0.041
5.39	3.84	4.45	4.95	100	100	0.0010	0.038	0.0007	0.037	0.0008	0.037	0.00100	0.041
5.33	3.80	4.40	4.89	150	50	0.0008	0.030	0.0006	0.032	0.0006	0.027	0.00080	0.033
5.29	3.77	4.37	4.85	200	0								
						MinE	0.030	MinE50	0.032	MinE100	0.027	MinE250	0.033
						MaxE	0.368	MaxE50	0.363	MaxE100	0.364	MaxE250	0.371

Appendix A

Uncertainty Analysis Results - EAD

D2575 = Difference between the 25% and 75% exceedance values in EAD distribution

Flow Frequency - Large EAD Distribution

N	EAD95	EAD75	EAD25	EAD5	D2575
200	0.05009	0.06012	0.07677	0.09060	0.01665
150	0.04818	0.05939	0.07805	0.09348	0.01866
140	0.04771	0.05922	0.07841	0.09421	0.01919
130	0.04712	0.05896	0.07868	0.09503	0.01972
120	0.04657	0.05872	0.07911	0.09609	0.02039
110	0.04585	0.05847	0.07965	0.09732	0.02118
100	0.04519	0.05812	0.08015	0.09880	0.02203
90	0.04425	0.05775	0.08083	0.10057	0.02308
80	0.04333	0.05743	0.08173	0.10257	0.02430
70	0.04209	0.05697	0.08284	0.10518	0.02587
60	0.04068	0.05634	0.08414	0.10853	0.02780
50	0.03885	0.05559	0.08597	0.11300	0.03038
40	0.03658	0.05465	0.08857	0.11948	0.03392
30	0.03341	0.05321	0.09255	0.12916	0.03934
20	0.02872	0.05108	0.09980	0.14750	0.04872
10	0.02059	0.04732	0.12000	0.19721	0.07268

Flow Frequency - Small EAD Distribution

N	EAD95	EAD75	EAD25	EAD5	D2575
200	0.06410	0.07584	0.0948	0.10997	0.01896
150	0.06178	0.07496	0.09625	0.11329	0.02129
140	0.06110	0.07470	0.09664	0.11423	0.02194
130	0.06038	0.07439	0.09697	0.11522	0.02258
120	0.05973	0.07412	0.09745	0.11647	0.02333
110	0.05886	0.07380	0.09803	0.11788	0.02423
100	0.05799	0.07339	0.09859	0.11952	0.02520
90	0.05692	0.07292	0.09943	0.12145	0.02651
80	0.05572	0.07249	0.10041	0.12378	0.02792
70	0.05418	0.07192	0.10166	0.12676	0.02974
60	0.05245	0.07114	0.10322	0.13040	0.03208
50	0.05015	0.07019	0.10524	0.13536	0.03505
40	0.04733	0.06904	0.10821	0.14245	0.03917
30	0.04327	0.06727	0.11273	0.15302	0.04546
20	0.03736	0.06463	0.12079	0.17256	0.05616
10	0.02679	0.05999	0.14292	0.22355	0.08293

Stage Flow - Large EAD Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.05009	0.06012	0.07677	0.09060	0.01665
0.3	0.04769	0.05921	0.07835	0.09427	0.01914
0.6	0.04186	0.05676	0.08193	0.10344	0.02517
1.5	0.02385	0.04671	0.09697	0.15029	0.05026
3.0	0.00834	0.03244	0.13001	0.26171	0.09757

Stage Flow - Small EAD Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.06410	0.07584	0.09480	0.10997	0.01896
0.3	0.03394	0.06079	0.11510	0.16817	0.05431
0.6	0.01298	0.04385	0.14811	0.26844	0.10426
1.5	0.00825	0.01708	0.27275	0.62846	0.25567
3.0	0.00788	0.01156	0.52491	0.94640	0.51335

Damage Stage - Large EAD Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.05009	0.06012	0.07677	0.09060	0.01665
5%	0.04865	0.05796	0.07288	0.08536	0.01492
10%	0.04684	0.05693	0.07368	0.08790	0.01675
20%	0.04005	0.05378	0.07641	0.09588	0.02263

Damage Stage - Small EAD Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.06410	0.07584	0.09480	0.10997	0.01896
5%	0.06224	0.07345	0.09101	0.10558	0.01756
10%	0.05977	0.07204	0.09220	0.10875	0.02016
20%	0.05076	0.06798	0.09576	0.11920	0.02778

Appendix A

Uncertainty Analysis Results - EAD With 50-yr Levee

D2575 = Difference between the 25% and 75% exceedance values in EAD distribution

Flow Frequency - Large EAD50 Distribution

N	EAD95	EAD75	EAD25	EAD5	D2575
200	0.01058	0.01465	0.02204	0.02896	0.00739
150	0.00968	0.01423	0.0228	0.03104	0.00857
140	0.00948	0.01413	0.02301	0.03167	0.00888
130	0.00922	0.01395	0.02322	0.03229	0.00927
120	0.00897	0.01381	0.02345	0.03304	0.00964
110	0.00869	0.01366	0.02376	0.03393	0.01010
100	0.00836	0.01348	0.02407	0.03500	0.01059
90	0.00800	0.01329	0.02448	0.03620	0.01119
80	0.00764	0.01310	0.02501	0.03759	0.01191
70	0.00718	0.01288	0.02569	0.03950	0.01281
60	0.00663	0.01255	0.02648	0.04181	0.01393
50	0.00596	0.01218	0.02759	0.04506	0.01541
40	0.00518	0.01173	0.02920	0.04992	0.01747
30	0.00420	0.01107	0.03174	0.05750	0.02067
20	0.00295	0.01012	0.03654	0.07250	0.02642
10	0.00309	0.00864	0.05091	0.11771	0.04227

Flow Frequency - Small EAD50 Distribution

N	EAD95	EAD75	EAD25	EAD5	D2575
200	0.01066	0.01484	0.02227	0.02935	0.00743
150	0.00976	0.01441	0.02307	0.03151	0.00866
140	0.00957	0.01430	0.02329	0.03205	0.00899
130	0.00932	0.01412	0.02349	0.03274	0.00937
120	0.00905	0.01399	0.02376	0.03352	0.00977
110	0.00878	0.01384	0.02406	0.03437	0.01022
100	0.00848	0.01365	0.02436	0.03545	0.01071
90	0.00811	0.01345	0.02476	0.03665	0.01131
80	0.00772	0.01326	0.02532	0.03807	0.01206
70	0.00726	0.01304	0.02598	0.03993	0.01294
60	0.00672	0.01271	0.02681	0.04230	0.01410
50	0.00606	0.01234	0.02791	0.04551	0.01557
40	0.00526	0.01188	0.02955	0.05044	0.01767
30	0.00425	0.01123	0.03211	0.05808	0.02088
20	0.00300	0.01024	0.03696	0.07321	0.02672
10	0.00314	0.00875	0.05142	0.11867	0.04267

Stage Flow - Large EAD50 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.01058	0.01465	0.02204	0.02896	0.00739
0.3	0.00987	0.01430	0.02243	0.03029	0.00813
0.6	0.00835	0.01348	0.02377	0.03428	0.01029
1.5	0.00405	0.01024	0.02995	0.05490	0.01971
3.0	0.00371	0.00674	0.04485	0.11826	0.03811

Stage Flow - Small EAD50 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.01066	0.01484	0.02227	0.02935	0.00743
0.3	0.00399	0.01033	0.03024	0.05469	0.01991
0.6	0.00344	0.00654	0.04485	0.11417	0.03831
1.5	0.00639	0.00939	0.11671	0.43500	0.10732
3.0	0.00720	0.01057	0.32422	0.89283	0.31365

Damage Stage - Large EAD50 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.01058	0.01465	0.02204	0.02896	0.00739
5%	0.01048	0.01459	0.02206	0.02920	0.00747
10%	0.01025	0.01440	0.02217	0.02964	0.00777
20%	0.00924	0.01370	0.02253	0.03133	0.00883

Damage Stage - Small EAD50 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.01066	0.01484	0.02227	0.02935	0.00743
5%	0.01061	0.01479	0.02231	0.02950	0.00752
10%	0.01038	0.01458	0.02245	0.03002	0.00787
20%	0.00933	0.01385	0.02278	0.03162	0.00893

Appendix A

Uncertainty Analysis Results - EAD With 100-yr Levee

D2575 = Difference between the 25% and 75% exceedance values in EAD distribution

Flow Frequency - Large EAD100 Distribution

N	EAD95	EAD75	EAD25	EAD5	D2575
200	0.00481	0.00712	0.01160	0.01611	0.00448
150	0.00435	0.00688	0.01209	0.01753	0.00521
140	0.00423	0.00682	0.01222	0.01795	0.00540
130	0.00410	0.00670	0.01234	0.01840	0.00564
120	0.00396	0.00663	0.01250	0.01893	0.00587
110	0.00380	0.00655	0.01270	0.01949	0.00615
100	0.00364	0.00645	0.01290	0.02025	0.00645
90	0.00348	0.00634	0.01317	0.02110	0.00683
80	0.00325	0.00619	0.01342	0.02197	0.00723
70	0.00305	0.00611	0.01394	0.02337	0.00783
60	0.00277	0.00592	0.01447	0.02510	0.00855
50	0.00242	0.00570	0.01519	0.02745	0.00949
40	0.00212	0.00547	0.01625	0.03103	0.01078
30	0.00161	0.00509	0.01797	0.03686	0.01288
20	0.00167	0.00462	0.02129	0.04876	0.01667
10	0.00236	0.00419	0.03171	0.08771	0.02752

Flow Frequency - Small EAD100 Distribution

N	EAD95	EAD75	EAD25	EAD5	D2575
200	0.00477	0.00709	0.01157	0.01612	0.00448
150	0.00432	0.00686	0.01204	0.01752	0.00518
140	0.00421	0.00677	0.01219	0.0179	0.00542
130	0.00406	0.00667	0.01231	0.01840	0.00564
120	0.00393	0.00660	0.01245	0.01892	0.00585
110	0.00377	0.00652	0.01266	0.01951	0.00614
100	0.00361	0.00641	0.01285	0.02023	0.00644
90	0.00346	0.00631	0.01312	0.02110	0.00681
80	0.00327	0.00620	0.01347	0.02207	0.00727
70	0.00303	0.00608	0.01389	0.02337	0.00781
60	0.00274	0.00590	0.01443	0.02507	0.00853
50	0.00240	0.00568	0.01513	0.02737	0.00945
40	0.00211	0.00544	0.01622	0.03098	0.01078
30	0.00159	0.00507	0.01791	0.03679	0.01284
20	0.00169	0.00461	0.02122	0.04867	0.01661
10	0.00239	0.00419	0.03160	0.08760	0.02741

Stage Flow - Large EAD100 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.00481	0.00712	0.01160	0.01611	0.00448
0.3	0.00454	0.00696	0.01186	0.01695	0.00490
0.6	0.00388	0.00661	0.0126	0.01920	0.00599
1.5	0.00184	0.00512	0.01623	0.03228	0.01111
3.0	0.00262	0.00385	0.02512	0.07334	0.02127

Stage Flow - Small EAD100 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.00477	0.00709	0.01157	0.01612	0.00448
0.3	0.00170	0.00497	0.01628	0.03235	0.01131
0.6	0.00249	0.00365	0.02526	0.07294	0.02161
1.5	0.00574	0.00843	0.07439	0.34174	0.06596
3.0	0.00702	0.01030	0.24075	0.83788	0.23045

Damage Stage - Large EAD100 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.00481	0.00712	0.01160	0.01611	0.00448
5%	0.00479	0.00708	0.01162	0.01617	0.00454
10%	0.00468	0.00700	0.01167	0.01643	0.00467
20%	0.00426	0.00667	0.01175	0.01717	0.00508

Damage Stage - Small EAD100 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.00477	0.00709	0.01157	0.01612	0.00448
5%	0.00474	0.00706	0.01157	0.01619	0.00451
10%	0.00464	0.00698	0.01166	0.01639	0.00468
20%	0.00426	0.00668	0.01178	0.01722	0.00510

Appendix A

Uncertainty Analysis Results - EAD With 250-Yr Levee

D2575 = Difference between the 25% and 75% exceedance values in EAD distribution

Flow Frequency - Large EAD250 Distribution

N	EAD95	EAD75	EAD25	EAD5	D2575
200	0.00177	0.00273	0.00491	0.00734	0.00218
150	0.00153	0.00263	0.00518	0.00814	0.00255
140	0.00147	0.00260	0.00525	0.00837	0.00265
130	0.00141	0.00255	0.00532	0.00864	0.00277
120	0.00134	0.00252	0.00542	0.00895	0.00290
110	0.00126	0.00248	0.00552	0.00928	0.00304
100	0.00121	0.00244	0.00561	0.00971	0.00317
90	0.00116	0.00238	0.00575	0.01022	0.00337
80	0.00112	0.00233	0.00592	0.01078	0.00359
70	0.00108	0.00227	0.00614	0.01160	0.00387
60	0.00104	0.00220	0.00643	0.01265	0.00423
50	0.00099	0.00207	0.00672	0.01394	0.00465
40	0.00096	0.00201	0.00740	0.01639	0.00539
30	0.00091	0.00181	0.00826	0.02006	0.00645
20	0.00101	0.00174	0.01028	0.02863	0.00854
10	0.00174	0.00255	0.01682	0.05898	0.01427

Flow Frequency - Small EAD250 Distribution

N	EAD95	EAD75	EAD25	EAD5	D2575
200	0.00177	0.00275	0.00493	0.00740	0.00218
150	0.00154	0.00264	0.00521	0.00820	0.00257
140	0.00148	0.00262	0.00529	0.00843	0.00267
130	0.00141	0.00257	0.00536	0.00872	0.00279
120	0.00135	0.00254	0.00545	0.00900	0.00291
110	0.00127	0.00250	0.00555	0.00933	0.00305
100	0.00121	0.00245	0.00565	0.00976	0.00320
90	0.00117	0.00240	0.00578	0.01030	0.00338
80	0.00113	0.00235	0.00596	0.01085	0.00361
70	0.00109	0.00229	0.00617	0.01164	0.00388
60	0.00105	0.00221	0.00647	0.01272	0.00426
50	0.00099	0.00208	0.00678	0.01403	0.00470
40	0.00096	0.00202	0.00744	0.01649	0.00542
30	0.00092	0.00182	0.00832	0.02019	0.0065
20	0.00104	0.00177	0.01034	0.02876	0.00857
10	0.00177	0.00259	0.01690	0.05922	0.01431

Stage Flow - Large EAD250 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.00177	0.00273	0.00491	0.00734	0.00218
0.3	0.00167	0.00269	0.00499	0.00767	0.00230
0.6	0.00136	0.00256	0.00534	0.00873	0.00278
1.5	0.00093	0.00186	0.00698	0.01534	0.00512
3.0	0.00165	0.00242	0.01132	0.03895	0.00890

Stage Flow - Small EAD250 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.00177	0.00275	0.00493	0.00740	0.00218
0.3	0.00091	0.00180	0.00720	0.01609	0.00540
0.6	0.00167	0.00245	0.01204	0.04150	0.00959
1.5	0.00499	0.00732	0.04158	0.24705	0.03426
3.0	0.00679	0.00996	0.16195	0.75691	0.15199

Damage Stage - Large EAD250 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.00177	0.00273	0.00491	0.00734	0.00218
5%	0.00175	0.00272	0.00491	0.00738	0.00219
10%	0.00173	0.00269	0.00493	0.00745	0.00224
20%	0.00159	0.00259	0.00499	0.00778	0.00240

Damage Stage - Small EAD250 Distribution

S	EAD95	EAD75	EAD25	EAD5	D2575
Base	0.00177	0.00275	0.00493	0.00740	0.00218
5%	0.00177	0.00274	0.00494	0.00745	0.00220
10%	0.00174	0.00270	0.00495	0.00750	0.00225
20%	0.00160	0.00260	0.00501	0.00784	0.00241